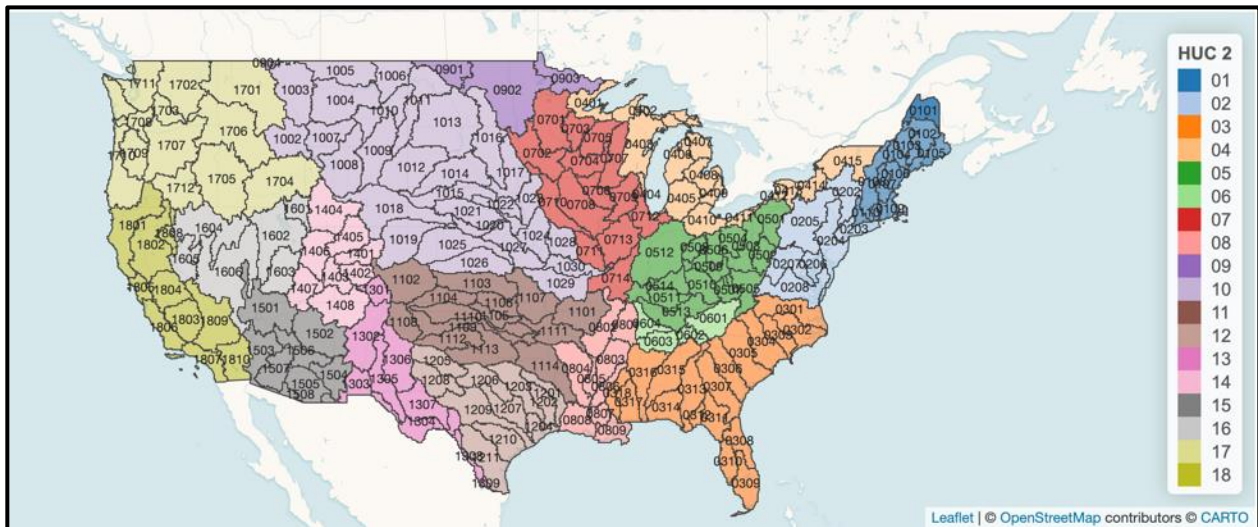# U.S. Army Corps of Engineers (USACE)
Climate Hydrology Assessment Tool (CHAT) User Guide

Version 2.3

User Guide
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U.S. Army Corps of Engineers, Washington, DC
Climate Preparedness and Resilience Community of Practice

Abstract:

Observations in recent decades indicate the climatological baseline and range of climate variability of meteorological conditions are shifting. Climate change is the large-scale shifts in weather patterns, due in part to human-driven activity such as changing land use and increasing carbon dioxide emissions. Changes in future climate conditions pose risks to current and future projects. The shift in weather patterns impacts the resilience of the U.S. Army Corps of Engineers (USACE) projects, programs missions, and operations and requires additional analysis to inform decisions throughout the lifecycle of projects. USACE developed the Climate Hydrology Assessment Tool (CHAT) to support analysis of potential, future changes in simulated hydrologic conditions. The CHAT supports Engineering and Construction Bulletin (ECB) 2018-14 requirements by facilitating standardized, appropriate, and efficient analysis of future, climate-influenced hydrologic variables. The purpose of this User Manual is to support the use of Version 2.3 of the CHAT released in December 2022. This User Manual is not intended to cover all situations one may encounter using the tool. The CHAT complements but is not a substitute for professional engineering judgment.

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1. Purpose/Background

Observations in recent decades indicate that the climatological baseline and range of climate variability of meteorological conditions are shifting. Climate change is the large-scale shifts in weather patterns, due in part to human-driven activity such as changing land use and increasing carbon dioxide emissions. Changes in future climate conditions pose risks to current and future projects. The shift in weather patterns impacts the resilience of USACE programs, projects, operations and missions and requires additional analysis to inform decisions over the lifetime of projects.

The USACE's framework for identifying, communicating and managing climate change related risk to inland hydrology applications is described in Engineering and Construction Bulletin (ECB) 2018-14 which can be found here: https://www.wbdg.org/ffc/dod/engineering-and-construction-bulletins-ecb/usace-ecb-2018-14. This guidance governs applications of climate change information for defining hydrologic impacts to USACE Civil Works projects. The analysis required by ECB 2018-14 focuses on changes in hydrologic variables relevant to the problems, opportunities, and alternatives being assessed as part of each USACE study. The guidance requires that changes in both historical and future/projected hydrology be taken into consideration. When analysis is being conducted in support of project design or modification, it is targeted at enabling the project development team (PDT) to incorporate climate change in the characterization of the Future Without Project condition and the Future With Project condition.

USACE's framework for analysis outlines three phases: Phase 1—Initial Scoping, Phase II—Vulnerability Assessment, and Phase III—Risk Assessment. USACE developed CHAT to support Phase II, where information is collected and analyzed to determine potential, future changes in simulated hydrologic conditions which will significantly affect USACE programs, projects, operations and/or missions. ECB 2018-14 recommends that changes to streamflow and meteorologic variables be assessed throughout the project lifecycle. For the majority of USACE projects, Engineering Regulations (ER) 1110-2-8159 and ER 1105-2-100 define the project lifecycle as 100 years (unless otherwise specified). ER 1110-2-8159 can be found at https://www.publications.usace.army.mil/Portals/76/Publications/EngineerRegulations/ER_1110-2-8159.pdf and ER 1105-2-100 can be found at https://www.publications.usace.army.mil/Portals/76/Publications/EngineerRegulations/er_1105-2-100.pdf.

USACE guidance requires study teams to use climate projections from Coupled Model Intercomparison Project, Phase 5 (CMIP5). The CHAT supports USACE teams in incorporating climate change information by enabling users to efficiently analyze modeled, historic, and future hydrology using a standardized and reproducible approach. The CHAT provides users with access to CMIP5-based simulations of meteorology and runoff, incorporating projections of greenhouse gas emissions. The CHAT provides simulated meteorological outputs for each 8-digit HUC basin in the continental United States (CONUS). The CHAT also provides simulated streamflow outputs for stream segments corresponding to the river routing network used to produce the runoff variable output displayed in the

tool. In addition to providing a visualization of the downscaled outputs from combinations of 32 different CMIP5 Global Climate Models (GCMs) and two representative concentration pathways of greenhouse gas emissions (RCPs 4.5 and 8.5), the tool also facilitates trend analysis and a comparative assessment of projected, epoch-based shifts in annual and monthly variables.

The purpose of this User Guide is to support the use of Version 2.3 of CHAT released in December 2022. This user guide reviews the GCM-based datasets incorporated into the tool, the methods applied by the tool, the tool's outputs and its user interface. This User Guide is not intended to cover all situations one may encounter using the tool. The USACE CHAT complements but is not a substitute for professional engineering judgment.

The Climate Hydrology Assessment Tool can be accessed at: https://climate.sec.usace.army.mil/chat/

2. Technical Background

Downscaled, GCM-based outputs displayed in this tool were processed using the open-source R statistical programming language. The tool was developed using R-Shiny. Users can view the results of simulations of both a historical period and a future (projected) period. In addition to providing visualizations of simulation results, the CHAT also presents a series of statistical metrics characterizing the simulated time series (i.e., magnitude, mean, range, trend analysis, epoch-based shifts in annual and monthly statistical properties). Model outputs are available for several meteorological variables at the 8-digit HUC basin level and for several runoff variables at the stream segment level. (See Section 2.1.3 for more details)

2.1. Data Sources

The CHAT uses output from GCM simulations from the CMIP5 product that have been statistically downscaled, and in the case of streamflow, translated into a runoff response using a hydrologic model and a river routing network. This section describes the data sources and methodologies used to generate the various hydrologic and meteorologic variables that are displayed in the CHAT.

2.1.1. LOCA-Downscaled GCM Output

The CHAT uses statistically downscaled outputs from 32 CMIP5 GCMs to generate visualizations of various, modeled streamflow and meteorologic simulations. Table 1 lists the 32 CMIP5 GCMs whose outputs are included in the CHAT. CMIP5 GCM outputs are available at a daily time step for calendar years 1950–2099. Historical period simulations span the timeframe 1950–2005, and future simulations span the timeframe 2006–2099. In the tool, the historical and future periods are defined as subsets of the GCM outputs. In the CHAT, the historical period is defined as water years 1951-2005 for the time series variables and defined as water years 1976-2005 for the robustness metric and epoch-based changes. The future period presented in the tool is defined as water years 2006-2099 for the time series variables and defined in terms of two future epochs for the robustness metric and epoch-based changes. The future

epochs used in the CHAT are the mid-century epoch spanning water years 2035-2064 and the end-century epoch spanning water years 2070-2099.

Historical simulations assume greenhouse gas emissions to be equivalent to a reconstruction of historically observed greenhouse gas emission levels. Note that although the GCM simulations for the historical period were conducted with the same reconstruction of historical greenhouse gas emission levels, outputs generated still vary due to differences in the representation of internal variability unique to each GCM simulation that is affected by differences in initial conditions, physical process representation, spatial resolutions, among others.

For future simulations, the CHAT applies simulations generated by assuming two different representative concentration pathways (RCPs, also known as "scenarios") of greenhouse gas emissions: RCP 4.5 and RCP 8.5. RCP 4.5 represents a rising, radiative forcing pathway stabilizing at 4.5 W/m^2 before 2100, and RCP 8.5 represents a rising, radiative forcing pathway leading to 8.5 W/m^2 in 2100. Radiative forcing expresses the change in energy in the atmosphere due to greenhouse gas emissions. See van Vuuren et al. (2011) for more detailed information on the development, assumptions, and characteristics of RCPs and guidance on the use of the RCPs.

Table 1: The 32 CMIP5 Global Climate Models Used to Derive the Model Output Variables Plotted in CHAT

ACCESS1-0	CMCC-CM	GFDL-ESM2M	IPSL-CM5A-MR
ACCESS1-3	CMCC-CMS	GISS-E2-H	MIROC5
bcc-csm1-1-m	CNRM-CM5	GISS-E2-R	MIROC-ESM-CHEM
bcc-csm1-1	CSIRO-Mk3-6-0	HadGEM2-AO	MIROC-ESM
CanESM2	EC-EARTH	HadGEM2-CC	MPI-ESM-LR
CCSM4	FGOALS-g2	HadGEM2-ES	MPI-ESM-MR
CESM1-BGC	GFDL-CM3	inmcm4	MRI-CGCM3
CESM1-CAM5	GFDL-ESM2G	IPSL-CM5A-LR	NorESM1-M

Native GCM outputs have too coarse of a resolution for many watershed or basin scale applications. Thus, the CHAT relies on CMIP5 GCM meteorological outputs that have been statistically downscaled using the Localized Constructed Analogs (LOCA) method (Pierce et al., 2014). These LOCA-downscaled GCM outputs provide simulated output at a spatial scale (1/16-degree resolution) that can be used in support of water resources applications. LOCA-downscaled GCM outputs presented in the CHAT are available online at: https://gdo-dcp.ucllnl.org/. Additional details about the set of GCM outputs and spatial downscaling method are documented in Pierce et al. (2014), and online at http://loca.ucsd.edu/. Table 2 describes the LOCA-downscaled GCM meteorologic variables used in CHAT: accumulated, daily precipitation, daily minimum temperature, daily average temperature, and daily maximum temperature.

Table 2: Meteorologic GCM-Based Outputs Used in CHAT

Variable	Abbreviation	Native Units	CHAT Customary Units	CHAT Metric Units
Near-surface, daily, accumulated precipitation *Note that this variable is the sum of liquid-rain and solid-ice/snow precipitation	"pr"	kg/m^2/s (a rate)	Converted to mm by multiplying by the number of seconds in a day then converted to accumulated daily inches (in)	Converted to accumulated daily millimeters (mm) by the number of seconds in a day
Near-surface daily minimum temperature	"tmin"	Kelvin (K)	Converted to degrees Fahrenheit (F)	Converted to degrees Celsius (C)
Near-surface, daily, average temperature	"tavg"	Kelvin (K)	Converted to degrees Fahrenheit (F)	Converted to degrees Celsius (C)
Near-surface daily maximum temperature	"tmax"	Kelvin (K)	Converted to degrees Fahrenheit (F)	Converted to degrees Celsius (C)

2.1.2. LOCA-VIC Model Output

The streamflow simulations displayed in the CHAT are generated in two steps. First, the meteorological variables are generated by the LOCA-downscaled, GCMs (described in Section 2.1.1). Then, the LOCA-downscaled, GCM-based meteorologic outputs are used as inputs to the Variable Infiltration Capacity (VIC) hydrologic model (VIC; Liang et al., 1996). The VIC hydrologic model was forced with those LOCA outputs to create a consistent portrayal of unregulated and largely uncalibrated areal runoff response across the CONUS. The University of Washington (UW) and Princeton University collaborated with several other researchers around the globe to develop the original VIC model. Development and maintenance of the current version of the VIC model is led by the UW Hydro Computational Hydrology Group (part of the UW Department of Civil and Environmental Engineering). The VIC hydrologic model represents unregulated basin conditions.

River routing is not included in the VIC model. The VIC model outputs gridded values of surface runoff and baseflow. Runoff and baseflow fluxes from VIC at the grid cell level were routed to and through a stream network using mizuRoute [Mizukami et al., 2016, doi: 10.5194/gmd-9-2223-2016]. The mizuRoute outputs are available for a network of 57,116 stream segments in CONUS and parts of Canada, individually denoted by segment identification (ID) numbers. The United States Geological Survey (USGS) Geospatial Fabric (GF) vector-based river network was used in the mizuRoute model to generate routed runoff (Viger, 2014). The mizuRoute model includes two routing schemes which are the Impulse Response Function (IRF) and the Kinetic Wave Tracking (KWT) algorithm. Only the IRF routed runoff is used in CHAT. In the mizuRoute framework, new segment IDs are typically generated when stream segments are interrupted (e.g., at the confluence of two streams).

Several stream segments have been filtered out of the dataset displayed in the tool. There were 284 stream segments that had no upstream drainage area in the mizuRoute network. As an artifact of this, the model returned all zeros for the routed runoff. Since these values are invalid, the stream segments in question have been removed from the CHAT. Additionally, all stream segments in Canada that did not intersect the US-Canada border were removed from the tool. After this filtering is applied, there are 59,608 stream segments presented in the tool.

The routed, LOCA-VIC model outputs displayed by the CHAT were generated by the Scripps Institution of Oceanography (http://loca.ucsd.edu/loca-vic-runs/). Routed VIC streamflow outputs are available for both the simulated, historical period of 1950–2005 and the future (projected) timeframe of 2006–2099. The routed output represents the daily, in-channel, runoff (i.e., average daily flowrate in m^3/s) for each stream segment in the mizuRoute network. The streamflow value associated with each stream segment is a representation of the total cumulative flow at the stream segment endpoint (node). The mizuRoute stream segments that corresponded to the terminal end of a river system (e.g., the last leg of a river before either going subsurface or flowing into a large body of water) are referred to as the "terminal downstream segments." The mizuRoute stream segments that either end near the downstream boundary of an 8-digit HUC basin or flow directly out of an 8-digit HUC basin are referred as "outlet stream segments."

Additional details about the streamflow simulations displayed by the CHAT are documented in Pierce et al. (2014), Livneh et al. (2013, 2015) and online at http://loca.ucsd.edu/. The LOCA-downscaled, GCM-based output translated into a runoff response using VIC are available online at https://gdo-dcp.ucllnl.org/. Table 3 describes the streamflow variables used in CHAT: daily mean streamflow and daily streamflow volume.

Table 3. GCM-Based Streamflow Outputs Used in CHAT

Variable	Native Units	CHAT Customary Units	CHAT Metric Units
Daily mean streamflow flux	m^3/s (a flowrate)	Converted to cubic feet per second (cfs)	Same units as the native units, cubic meters per second (cms)
Daily streamflow volume	m^3/s (a flowrate)	Converted to daily volume by multiplying by the number of seconds in a day then converted to accumulated million acre-feet (maf)	Converted to daily volume by multiplying by the number of seconds in a day then converted to accumulated cubic kilometers (ckm)

2.1.3. HUC Basin Boundaries

Shapefiles delineating HUC basin boundaries were obtained from the NHDPlus National Data website (https://www.epa.gov/waterdata/nhdplus-national-data) circa 2016. Shapefiles from the Watershed Boundary Dataset (NHDPlusV21_NationalData_WBDSnapshot_Shapefile_08.7z) were aggregated to the

8-digit and 4-digit HUC basin levels. Boundary geometries were subsampled, reducing the shapefile resolution. Additional information about the dataset can be found in the NHDPlus Version 2: User Guide (McKay et al., 2012).

HUC basins can overlap international boundaries (e.g., there are HUC basins in the northern United States that include parts of southern Canada), which means that data for those basins on the international borders potentially includes information that is not exclusive to the CONUS.

In the CHAT, basins crossing the U.S.-Canada and U.S.-Mexico borders are bounded to the areal regions within the United States. The data presented in the tool reflect these basin boundaries (i.e., only data falling within the U.S. portion of a basin are presented). However, this has no effect on the underlying data and is only for display purposes. The border file was downloaded from the U.S. Census Cartographic Boundary Files dataset (https://www.census.gov/geographies/mapping-files/time-series/geo/carto-boundary-file.html; cb_2018_us_nation_20m.zip). Naming conventions for the 4-digit HUC basins and most of the 8-digit HUC basins are defined by the Watershed Boundary Dataset. Supplementary 8-digit HUC basin name assignments follow USGS Water Resources List (https://water.usgs.gov/GIS/huc_name.html) when the U.S. Census Cartographic Boundary Files dataset did not have a name associated with the 8-digit HUC basin.

Note that the HUC basin boundaries are frequently updated by the United States Geological Survey (USGS), in collaboration with the Environmental Protection Agency (EPA) to reflect new information. As a result, users may encounter differences between the 8-digit HUC basin boundaries in the CHAT and more recently updated versions of the Watershed Boundary Dataset reported on external sites hosted by other agencies (e.g., USGS). On rare occasions, users may encounter a situation where they are not able to find their 8-digit HUC basin of interest due to a name change or a significant shift in a basin's delineation. Please contact CPR support (cprsupport@usace.army.mil) for any specific inquiries about the HUC basin boundaries and naming conventions applied.

2.2. Processing Methodologies

Various hydrologic variables were derived from the sources described above. This section describes the methodologies used to generate the variables that are displayed in the CHAT. There are separate sections to describe the processing for streamflow variables versus the temperature and precipitation variables. Annual time series, annual epoch-based changes, and monthly epoch-based changes were calculated for each data type (i.e., streamflow, temperature, and precipitation).

The CHAT allows the user to visualize all time series outputs for either of the two future RCP scenarios separately as well as for both future scenarios together overlaid onto the same plot. All annual variables are calculated per water year. A water year spans October 1 of the previous year through September 30 of the current year. For example, water year 2000 spans October 1, 1999 through September 30, 2000. The monthly variables are also calculated with respect to water year. For example, monthly variables calculated for the mid-century epoch include data from all months that fall between October 2034 through September 2064 which covers water years 2035-2064. Similarly, monthly variables for the end-century

epoch include data that fall between October 2069 through September 2099 which covers water years 2070-2099.

2.2.1. Streamflow Variable Processing

The processing steps taken to generate the routed runoff variables displayed in the CHAT are described in this section.

Streamflow variables can be viewed on a an 8-digit HUC level or a stream segment within an individual 8-digit HUC. If HUC level data is desired, as previously seen in CHAT v2.2, the data from the HUC's terminal stream segment should be selected. To enable users to easily view streamflow output at an 8-digit HUC level, the terminal stream segment for each HUC is identified within the CHAT's *Study Location Selector* Tab. To identify the terminal stream segment associated with each 8-digit HUC, a shapefile-based delineation of the stream segments contained in the CONUS-wide mizuRoute routing network (described in Section 2.1.2) was overlaid with the 8-digit HUC basin boundary shapefile (described in Section 2.1.3) using a geographic information system (GIS).

Each stream segment is tied to streamflow output from the VIC-mizuRoute models. Reported runoff at each stream segment represents cumulative outflow. Cumulative outflow includes in-channel, routed flow from all upstream segments including flow from contributing, upstream 8-digit HUC basins. The terminal and outlet stream segments associated with the downstream most boundary of each 8-digit HUC basin are identified as being representative of the cumulative flow exiting each 8-digit HUC basin.

There are 2,111 8-digit HUC basins in the CONUS. A manual crosswalk was performed between stream segments and 8-digit HUC basin boundaries to identify the segment that most closely represented the outlet of each 8-digit HUC basin. Two hundred and three 8-digit HUC basins contain two or more potential terminal and/or outlet stream segments. This is because the terminal, downstream and outlet stream segment endpoints do not always line up perfectly with the most downstream 8-digit HUC basin boundary. Confluence points just inside a given 8-digit HUC basin and parallel stream systems which transect a HUC basin boundary in close proximity can create ambiguity. For the 203 8-digit HUC basins with more than one potential terminal or outlet stream segment, the segment with the largest cumulative, daily flow over the 1950-2099 period was identified for each of the 64 GCM-RCP combination. The stream segment chosen most often across all 64 streamflow simulations was then chosen as the HUC's terminal stream segment. This is the segment identified as the terminal segment within the *Study Location Selector* Tab.

Note that some 8-digit HUC basins did not contain any outflow stream segments or the downstream-most terminal or outlet segment had zero flow. This is usually either because the basin is very dry (e.g., desert areas) or because the basin encompasses a body of water (e.g., bay areas or lakes). If an 8-digit HUC basin with zero flow is selected on the *Study Location Selector* tab, the user will be notified via a pop-up box with the message:

"This 8-digit HUC does not have any aligned stream segments, but meteorological outputs are available for the selected the 8-digit HUC.

Click *Go to Plot* to view meteorological outputs on subsequent tabs."

2.2.1.1. *Annual Streamflow Variable Time Series Processing*

Simulated, annual streamflow outputs displayed in the CHAT are available for water years 1951–2005 representing the historical timeframe and for water years 2006–2099 representing the future timeframe. Additional notes about water years 1951 and 2006 can be found in Section 2.3. Table 4 details the annual timescale aggregation process for the simulated streamflow output.

Table 4: CHAT Streamflow Time Series Variable Details

Variable Name	Units	Processing Steps
Annual-Mean 1-day Streamflow	Cubic Feet per Second (cfs) or Cubic Meters per Second (cms)	1) Define the mean daily average streamflow for each stream segment. 2) Take the mean of the daily average streamflow per each water year between 1951 and 2099. 3) Calculate the inter-model statistics.
Annual-Maximum of Mean Monthly Streamflow	Cubic Feet per Second (cfs) or Cubic Meters per Second (cms)	1) Define the mean daily average streamflow for each stream segment. 2) Take the mean of the daily average streamflow over each month. 3) Take the maximum of the monthly means per each water year between 1951 and 2099. 4) Calculate the inter-model statistics.
Annual Streamflow Volume	Million Acre Feet (maf) or Cubic Kilometers (ckm)	1) Define the mean daily average streamflow for each stream segment. 2) Convert streamflow from a flowrate to an accumulated sum per day (by multiplying the flowrate by the number of seconds in a day). 3) Take the sum of daily accumulated streamflow per each water year between 1951-2099. 4) Calculate the inter-model statistics.

The resulting simulations of annual streamflow-based metrics are available for all 64 combinations of GCMs and RCPs. The inter-model statistics (i.e., minimum, maximum, and mean) are calculated across the 32 GCMs for each stream segment, separately for the two RCPs. The information that is displayed in the CHAT represents the inter-model variability of simulated historical and future values for each variable.

Note that the annual-maximum of monthly mean streamflow variable is not directly equivalent to peak annual flow. The associated annual maximum has been smoothed considerably by first taking the mean of the monthly flows.

2.2.1.2. Annual Variable Epoch-Based Percent Change Processing

Epoch-based percent change was also calculated for the annual variables. After defining the daily streamflow model outputs for each stream segment, the following variables are generated: annual mean streamflow, annual maximum of monthly mean streamflow, and annual accumulated sum of streamflow. The steps taken to generate epoch-based percent change of these annual streamflow variables are described in Table 5.

Annual comparisons are produced by defining means of the annual variable over three time periods referenced as "epochs." The three epochs defined within the CHAT are: 1) the Base epoch, defined as water years 1976–2005, 2) the Mid-Century epoch, defined as water years 2035–2064, and 3) the End-Century epoch, defined as water years 2070–2099. The percent change between epoch-mean values for two epochs is computed to define simulated percent change in the streamflow variable overtime.

The percent changes in the simulated streamflow epoch-mean displayed in the CHAT are computed between the Base epoch and the Mid-Century epoch, as well as between the Base epoch and End-Century epoch for RCPs 4.5 and 8.5. Percent change is defined as the difference between the future epoch and Base epoch means divided by the Base epoch mean.

In the CHAT, the epoch-mean differences between the two future periods and the base (historic) epoch are displayed as box plots. There is one box plot displayed per epoch-scenario combination for the annual epoch-based percent change variables. Box plots provide a visualization of various inter-model statistics, beyond just the mean and range displayed for the annual time series variables described in Table 4. Please see the CHAT Application section for more details related to the statistical properties represented by the box plots.

Table 5: CHAT Streamflow Annual Epoch-Based Changes Variable Details

Variable Name	Units	Processing Steps
Percent Change in Mean Annual Streamflow	Unitless	1) Define the mean daily average streamflow for each stream segment. 2) Take the mean of the daily average streamflow per each water year between 1976 and 2099. 3) Calculate the epoch-means of the annual values. 4) Calculate the percent differences between the future and historical epochs. 5) Calculate the inter-model statistics.
Percent Change in Mean Annual-Maximum Monthly Mean Streamflow	Unitless	1) Define the mean daily average streamflow for each stream segment. 2) Take the mean of the daily average streamflow over each month. 3) Take the maximum of the monthly means per each water year between 1976 and 2099. 4) Calculate the epoch-means of the annual values. 5) Calculate the percent differences between the future and historical epochs. 6) Calculate the inter-model statistics.
Percent Change in Mean Annual-Streamflow Volume	Unitless	1) Define the mean daily average streamflow for each stream segment. 2) Convert streamflow from a discharge rate to an accumulated sum per day (by multiplying the discharge rate in cubic feet per second by the number of seconds in a day). 3) Take the sum of daily accumulated streamflow per each water year between 1976-2099. 4) Calculate the epoch-means of the annual values. 5) Calculate the percent differences between the future and historical epochs. 6) Calculate the inter-model statistics.

2.2.1.3. *Monthly Variable Epoch-Based Percent Change Processing*

In addition to aggregating the GCM-based output by water year, the simulated model outputs are also analyzed comparatively at a monthly timescale. After defining the daily streamflow model outputs for each stream segment, the following variables are generated: monthly mean streamflow and monthly accumulated streamflow. The steps taken to generate these monthly streamflow variables are described in Table 6.

Monthly comparisons are produced by defining monthly means over the same three epochs defined in Section 2.2.1.2 for the epoch-based changes of annual variables. The percent change between epoch-mean values for two epochs are computed to define simulated change in the streamflow variable over time.

The simulated percent changes in the streamflow epoch-mean displayed in the CHAT are computed between the Base epoch and the Mid-Century epoch, as well as between the Base epoch and End-Century epoch for RCPs 4.5 and 8.5. Percent change is defined as the difference between the future epoch and Base epoch means divided by the Base epoch mean.

For the monthly variables, epoch-based percent changes are calculated for each month of a year. For example, the mean of all monthly values calculated for each January within the Base epoch is calculated and the mean of all January values for the Mid-Century epoch is calculated. The percent change between these values becomes the Mid-Century epoch-based change for January.

In the CHAT, the epoch-mean percent changes between the two future periods and the base (historic) epoch for streamflow variables are displayed as box plots. There are 12 box plots displayed per epoch-scenario combination, representing a percentage change calculated for each month. Please see the CHAT Application section for more details related to the statistical properties represented by the box plots.

Table 6: CHAT Streamflow Monthly Epoch-Based Changes Variable Details

Variable Name	Units	Processing Steps
Percent Change in Mean Monthly Streamflow	Unitless	1) Define the mean daily average streamflow for each stream segment. 2) Take the mean of the daily average streamflow per each month. 3) Calculate the epoch-means of the monthly values. 4) Calculate the percent differences between the future and historical epochs for each month. 5) Calculate the inter-model statistics.
Percent Change in Mean Monthly-Streamflow Volume	Unitless	1) Define the mean daily average streamflow for each stream segment. 2) Convert streamflow from a discharge rate to an accumulated sum per day (by multiplying the discharge rate in cubic feet per second by the number of seconds in a day). 3) Take the sum of daily accumulated streamflow per each month. 4) Calculate the epoch-means of the monthly values. 5) Calculate the percent differences between the future and historical epochs. 6) Calculate the inter-model statistics.

2.2.2. Temperature and Precipitation Variable Processing

The LOCA-downscaled GCM output is aggregated to the 8-digit HUC basin level. For a given variable (e.g., maximum daily temperature), the modeled, gridded meteorologic output is overlaid with the 8-digit HUC basin boundary shapefile. The values for grid cells that fall within a given 8-digit HUC basin are

extracted and averaged to generate aggregated, daily values for each 8-digit HUC basin. A grid cell is assigned to an 8-digit HUC basin if its center point falls within that 8-digit HUC basin's boundary.

The processing steps taken to generate the multiple temperature and precipitation variables displayed in the CHAT for the modeled annual time series, annual epoch-based changes, and monthly epoch-based changes are described below.

2.2.2.1.   *Annual Variable Time Series Processing*

Downscaled, simulated temperature and precipitation output generated using GCMs is aggregated to an annual timescale as detailed in Table 7 and
Table 8. GCM based, simulated, annual temperature and precipitation outputs displayed in the CHAT are available for water years 1951–2005 representing the historical timeframe and for water years 2006–2099 representing the future timeframe. Additional notes about water years 1951 and 2006 are available in Section 2.3.

The resulting annual temperature- and precipitation-based variable output is available for all 64 combinations of GCMs and RCPs. The inter-model statistics (i.e., minimum, maximum, and mean) are calculated using downscaled output from the 32 CMIP5 GCMs for each 8-digit HUC basin, separately for the two RCPs. The information that is displayed in the CHAT represents the inter-model variability of simulated historical and future values for each variable.

Note that the "Drought Indicator" variable is a discrete variable (i.e., integer). When that variable is aggregated across models to generate the inter-model mean, it creates the illusion that the variable is continuously valued (i.e., the mean of a discretely valued quantity can be a non-integer value).

Table 7: CHAT Temperature Time Series Variable Details

Variable Name	Units	Processing Steps
Annual-Minimum 1-day Temperature	Degrees Fahrenheit (° F) or Degrees Celsius (° C)	1) Define the mean daily minimum temperature for each 8-digit HUC basin. 2) Take the minimum of the daily average temperature over each water year between 1951 and 2099. 3) Calculate the inter-model statistics.
Annual-Mean 1-day Temperature	Degrees Fahrenheit (° F) or Degrees Celsius (° C)	1) Define the mean daily average temperature for each 8-digit HUC basin. 2) Take the mean of the daily average temperature over each water year between 1951 and 2099. 3) Calculate the inter-model statistics.
Annual-Maximum 1-day Temperature	Degrees Fahrenheit (° F) or Degrees Celsius (° C)	1) Define the mean daily maximum temperature for each 8-digit HUC basin. 2) Take the maximum of the daily maximum temperature over each water year between 1951 and 2099. 3) Calculate the inter-model statistics.

Table 8: CHAT Precipitation Time Series Variable Details

Variable Name	Units	Processing Steps
Annual-Accumulated Precipitation	Inches (in) or Millimeters (mm)	1) Define the mean daily accumulated precipitation for each 8-digit HUC basin. 2) Calculate the summation of the daily accumulated precipitation over each water year between 1951 and 2099. 3) Calculate the inter-model statistics.
Annual-Maximum 1-day Precipitation	Inches (in) or Millimeters (mm)	1) Define the mean daily accumulated precipitation for each 8-digit HUC basin. 2) Take the maximum of the daily accumulated precipitation over each water year between 1951 and 2099. 3) Calculate the inter-model statistics.
Annual-Maximum 3-day Precipitation	Inches (in) or Millimeters (mm)	1) Define the mean daily accumulated precipitation for each 8-digit HUC basin. 2) Take the rolling 3-day sum of the daily accumulated precipitation time series between 1951 and 2099. 3) Take the maximum rolling 3-day sum over each water year. 4) Calculate the inter-model statistics.
Drought Indicator: Annual-Maximum of Number of Consecutive Dry Days	Number of Days	1) Define the mean daily accumulated precipitation for each 8-digit HUC basin. 2) Identify the number of dry days (days with precipitation less than 0.01 inches or 0.254 mm) in the daily accumulated precipitation time series spanning from 1951–2099. 3) Calculate the maximum number of consecutive dry days over each water year. 4) Calculate the inter-model statistics.

1.1.1.1.   Annual Variable Epoch-Based Changes Processing

Epoch-based changes were also calculated for the annual variables. The steps to generate the epoch-based changes of annual temperature and precipitation variables are described in Table 9 and Table 10, respectively.

Table 9: CHAT Annual Temperature Epoch-Based Variable Details

Variable Name	Units	Processing Steps
Change in Annual-Minimum Temperature	Degrees Fahrenheit (° F) or Degrees Celsius (° C)	1) Define the mean daily minimum temperature for each 8-digit HUC basin. 2)Take the minimum of the daily minimum temperature per each water year. 3) Calculate the epoch-means of the annual values. 4) Calculate the differences between the future and historical epochs. 5) Calculate the inter-model statistics.

Change in Annual-Mean Temperature	Degrees Fahrenheit (° F) or Degrees Celsius (° C)	1) Define the mean daily average temperature for each 8-digit HUC basin. 2) Take the mean of the daily average temperature per each water year. 3) Calculate the epoch-means of the annual values. 4) Calculate the differences between the future and historical epochs. 5) Calculate the inter-model statistics.
Change in Annual-Maximum Temperature	Degrees Fahrenheit (° F) or Degrees Celsius (° C)	1) Define the mean daily maximum temperature for each 8-digit HUC basin. 2)Take the maximum of the daily maximum temperature per each water year. 3) Calculate the epoch-means of the annual values. 4) Calculate the differences between the future and historical epochs. 5) Calculate the inter-model statistics.

Table 10: CHAT Annual Precipitation Epoch-Based Variable Details

Variable Name	Units	Processing Steps
(Percent) Change in Annual-Accumulated Precipitation	Inches (in) or Millimeters (mm); Unitless for Percent Change	1) Define the mean daily accumulated precipitation for each 8-digit HUC basin. 2) Take the sum of the daily accumulated precipitation per each water year. 3) Calculate the epoch-means of the annual values. 4) Calculate the (percent) differences between the future and historical epochs. 5) Calculate the inter-model statistics.
(Percent) Change Annual-Maximum 1-day Precipitation	Inches (in) or Millimeters (mm); Unitless for Percent Change	1) Define the mean daily accumulated precipitation for each 8-digit HUC basin. 2) Take the maximum of the daily accumulated precipitation per each water year. 3) Calculate the epoch-means of the annual values. 4) Calculate the (percent) differences between the future and historical epochs. 5) Calculate the inter-model statistics.
(Percent) Change in Annual-Maximum 3-day Precipitation	Inches (in) or Millimeters (mm); Unitless for Percent Change	1) Define the mean daily accumulated precipitation for each 8-digit HUC basin. 2) Take the rolling 3-day sum of the daily accumulated precipitation. 3) Take the maximum rolling 3-day sum per each water year. 4) Calculate the epoch-means of the annual values. 5) Calculate the (percent) differences between the future and historical epochs. 6) Calculate the inter-model statistics.

(Percent) Change in Drought Indicator	Number of Days; Unitless for Percent Change	1) Define the mean daily accumulated precipitation for each 8-digit HUC basin. 2) Identify the number of dry days (days with precipitation less than 0.01 inches or 0.254 mm) in the daily accumulated precipitation time series spanning from 1976–2099. 3) Calculate the maximum number of consecutive dry days per each water year. 4) Calculate the epoch-means of the annual values. 5) Calculate the (percent) differences between the future and historical epochs. 6) Calculate the inter-model statistics.

Annual comparisons are produced by defining means of the annual variable over three time periods referenced as "epochs." The three epochs defined within the CHAT are: 1) the Base epoch, defined as water years 1976–2005, 2) the Mid-Century epoch, defined as water years 2035–2064, and 3) the End-Century epoch, defined as water years 2070–2099. The difference between epoch-mean values for two epochs are computed to define simulated change in a given meteorologic variable over time. There is one difference calculated per epoch-scenario combination.

The simulated changes in the temperature and precipitation epoch-mean displayed in the CHAT are computed between the Base epoch and the Mid-Century epoch, as well as between the Base epoch and End-Century epoch for RCPs 4.5 and 8.5. For all precipitation variables, epoch-based percent change is also calculated. Percent change is defined as the difference between the future epoch and Base epoch means divided by the Base epoch mean. Standard practice for presenting changes in temperature is to present absolute changes because temperature is not a measure quantity. Thus, epoch-based percent change is not provided for temperature variables.

In the CHAT, the epoch-mean differences between the two future periods and the base (historic) epoch are displayed as box plots. There is one box plot displayed per epoch-scenario combination. Box plots provide a visualization of various inter-model statistics, beyond just the mean and range displayed for the annual time series variables described in Table 7 and
Table 8. Please see the CHAT Application section for more details related to the statistical properties represented by the box plots.

2.2.2.2. *Monthly Variable Epoch-Based Changes Processing*

In addition to aggregating the GCM-based output by water year, simulated model outputs are also analyzed comparatively at a monthly timescale. After defining the daily temperature model outputs for each 8-digit HUC basin, the following variables are generated: monthly minimum daily temperature, monthly maximum daily temperature, and monthly mean daily temperature. The steps taken to generate these monthly temperature variables are described in Table 11. Similarly, after the daily precipitation model outputs are generated per 8-digit HUC, the following variables are generated: monthly accumulated precipitation, monthly maximum daily precipitation, and monthly maximum of a 3-day

rolling sum of precipitation. The steps taken to generate the monthly precipitation variables are described in Table 12.

Table 11: CHAT Monthly Temperature Epoch-Based Variable Details

Variable Name	Units	Processing Steps
Change in Monthly-Minimum Temperature	Degrees Fahrenheit (° F) or Degrees Celsius (° C)	1) Define the mean daily minimum temperature for each 8-digit HUC basin. 2)Take the minimum of the daily minimum temperature per each month. 3) Calculate the epoch-means of the monthly values. 4) Calculate the differences between the future and historical epochs. 5) Calculate the inter-model statistics.
Change in Monthly-Mean Temperature	Degrees Fahrenheit (° F) or Degrees Celsius (° C)	1) Define the mean daily average temperature for each 8-digit HUC basin. 2) Take the mean of the daily average temperature per each month. 3) Calculate the epoch-means of the monthly values. 4) Calculate the differences between the future and historical epochs. 5) Calculate the inter-model statistics.
Change in Monthly-Maximum Temperature	Degrees Fahrenheit (° F) or Degrees Celsius (° C)	1) Define the mean daily maximum temperature for each 8-digit HUC basin. 2)Take the maximum of the daily maximum temperature per each month. 3) Calculate the epoch-means of the monthly values. 4) Calculate the differences between the future and historical epochs. 5) Calculate the inter-model statistics.

Table 12: CHAT Monthly Precipitation Epoch-Based Variable Details

Variable Name	Units	Processing Steps
(Percent) Change in Monthly-Accumulated Precipitation	Inches (in) or Millimeters (mm); Unitless for Percent Change	1) Define the mean daily accumulated precipitation for each 8-digit HUC basin. 2) Take the sum of the daily accumulated precipitation per each month. 3) Calculate the epoch-means of the monthly values. 4) Calculate the (percent) differences between the future and historical epochs. 5) Calculate the inter-model statistics.
(Percent) Change in Monthly-Maximum 1-day Precipitation	Inches (in) or Millimeters (mm); Unitless for Percent Change	1) Define the mean daily accumulated precipitation for each 8-digit HUC basin. 2) Take the maximum of the daily accumulated precipitation per each month. 3) Calculate the epoch-means of the monthly values. 4) Calculate the (percent) differences between the future and historical epochs. 5) Calculate the inter-model statistics.
(Percent) Change in Monthly Maximum 3-Day Precipitation	Inches (in) or Millimeters (mm); Unitless for Percent Change	1) Define the mean daily accumulated precipitation for each 8-digit HUC basin. 2) Take the rolling 3-day sum of the daily accumulated precipitation. 3) Take the maximum rolling 3-day sum per each month. 4) Calculate the epoch-means of the monthly values. 5) Calculate the (percent) differences between the future and historical epochs. 6) Calculate the inter-model statistics.

Monthly comparisons are produced by defining monthly means over the same three epochs defined in Section 1.1.1.1 for the epoch-based changes of annual variables which are historical (1976-2005), mid-century (2035-2064), and end-century (2070-2099). Simulated change in a given meteorologic variable over time is defined by the difference between epoch-mean values of two epochs.

The simulated changes in the temperature and precipitation epoch-mean displayed in the CHAT are computed between the Base epoch and the Mid-Century epoch, as well as between the Base epoch and End-Century epoch for RCPs 4.5 and 8.5. For all precipitation variables, epoch-based percent change is also calculated. Percent change is defined as the difference between the future epoch and Base epoch means divided by the Base epoch mean. Epoch-based percent change is not available for the temperature variables.

For the epoch-based changes of monthly variables, differences are calculated for each month of a year. For example, the mean of all monthly variables calculated for each January within the Base epoch is calculated and the mean of all January variables for the Mid-Century epoch is calculated. The difference between these values becomes the Mid-Century epoch-based change for January.

In the CHAT, the epoch-mean differences between the two future periods and the base (historic) epoch are displayed as box plots. There are 12 box plots displayed per epoch-scenario combination, representing a difference calculated for each month. Please see the CHAT Application section for more details related to the statistical properties represented by the box plots.

2.2.3. Simulated Annual Time Series Trend Analysis

In addition to providing aggregate statistics (i.e., inter-model minimum, maximum and mean) for the annual time series variables, the CHAT evaluates whether there is evidence of a statistically significant trend in the mean of the 32 GCM simulated time series for both the historical simulation period (i.e., water years 1951–2005) and the future simulation period (i.e., water years 2006–2099), separately for the two RCPs.

The tool presents a linear regression line and its associated slope for each subset of model output variables, as well as an evaluation of whether the indicated, simulated trendline is statistically significant (i.e., non-zero) for the historical period and the selected future scenario. The statistical significance of the simulated trendline is evaluated using the Student's t-test, the Mann-Kendall test, and the Spearman Rank-Order test. Various values of the significance threshold (i.e., alpha) can be selected for analysis, depending on several factors (see EM 200-1-16 for more detail). EM 200-1-16 is available online at https://www.publications.usace.army.mil/Portals/76/Publications/EngineerManuals/EM_200-1-16.pdf. To be consistent with published statistical standards, the CHAT uses a default significance level of 0.05 for the Student's t-test, Mann-Kendall test, and Spearman Rank-Order test (Fisher, 1934). This implies that trends with computed p-values less than or equal to 0.05 will be considered significant. A significance level of 0.05 translates to a 5% probability of encountering a false positive (Type I error) which means rejecting the null hypothesis given that the null hypothesis is true (e.g., identifying a significant trend when there is no significant trend). In other words, setting the significance level at a certain value predetermines the probability of a Type I error. It is unlikely, but possible for some but not all of the tests to identify a statistically significant trend (p-value <= 0.05). Below is a more detailed description of the metrics used in the tool:

1. **Regression Line Slope**: The slope of each trend can provide the directionality (e.g., increasing or decreasing) of the trend. The slope of the trendline also provides an indication of the magnitude of rate of change overtime. For example, slope can be used to determine whether the percent change in a given variable over a 50-year or 100-year period (for example) is operationally relevant. The further the slope is from zero (either positive or negative), the larger the magnitude of change is. A linear regression equation is fitted to the data using ordinary least squares as described in Chambers (1992) and Wilkinson (1973) to calculate slope.
2. **Student's t-test**: The Student's t-test is a parametric hypothesis test that relies on the assumption of normality. A p-value from a t-test is computed to determine whether two sets of data are significantly different from each other. The computed p-value represents a measurement comparing the strength of the signal (i.e., sample mean – population mean) to the variation of the data (i.e., the noise of the data). The smaller the magnitude of the p-value, the greater the chance of rejecting the null hypothesis (e.g., where the null hypothesis is defined as no trend being present). A large p-value would suggest that it is highly unlikely that a trend exists. For more information, please see Chambers (1992).

3. **Mann-Kendall**: Mann-Kendall is a non-parametric hypothesis test applied to determine the presence of a monotonic trend, defined as a consistently increasing or decreasing trend. A p-value is computed to determine whether a monotonic trend exists in the dataset. Data is listed in the order they were collected (over time). Differences are taken between pairs of data points $x_j - x_k$ where $j > k$ and the sum of the sign of differences is calculated (where the sign is either -1, 0, or 1 if the difference is negative, zero, or positive respectively) then used to calculate the Kendall rank correlation coefficient. The Mann-Kendall trend test uses the Kendall rank correlation of a time series to determine if a monotonic trend is present in the dataset. Results presented in the CHAT are based on a calculation of the two-sided p-value using the methods described in Hipel and McLeod (2005) and Mann (1945).
4. **Spearman Rank-Order**: The Spearman Rank-Order test is another non-parametric measure to determine whether there is a monotonic association between two ranked variables (e.g., time and the measurement of interest). A p-value is computed to determine whether a monotonic trend exists in the dataset. Both variables in the dataset are ranked separately (in monotonic order) then the Spearman's rho statistic is calculated using the paired ranks to estimate a rank-based measure of monotonic association between samples (Best and Roberts, 1975). A test to determine whether the Spearman's rho value is zero (indicating no monotonic trend) is then performed which results in a p-value. The p-value associated with the Spearman Rank-Order test is computed according to the methodology described in Hollander and Wolfe (1973).

2.2.4. Robustness Metrics

In the Sixth Assessment Report (AR6) released by the Intergovernmental Panel on Climate Change (IPCC), there are a few methods described for how to assess the robustness of a trend (https://www.ipcc.ch/assessment-report/ar6/). These methods can be found in the Atlas of the Working Group 1: The Physical Science Basis portion of the IPCC's AR6. CHAT v2.3 focuses on an approach that can be applied to model-based projections and assesses agreement between the projections generated using different GCMs in terms of the directionality of change and whether the signal emerges from the historical variability. The signal is considered to have emerged from the historical variability if the projected change exceeds the modeled, historical variability threshold.

The first component contributing to the robustness metric assesses whether there is agreement on the direction of change between the historical and future periods across most models. Specifically, these steps were completed to assess agreement of the sign of change:

1. For each of the 32 model-based simulations, calculate the change between epochs:
    a. Calculate the historical mean value, $\mu_{historical}$, of an annual variable for the 30-year epoch spanning years 1976-2005.
    b. Calculate the future mean value, μ_{future}, of an annual variable for the 30-year epoch spanning years 2035-2064 for the mid-century or spanning years 2070-2099 for the end-century.
    c. Take the difference between the means, $\Delta = \mu_{future} - \mu_{historical}$
2. If ≥80% (over 25) of models agree on the sign of change (i.e., whether Δ is positive or negative), then there is agreement amongst the models in terms of directionality of change. Otherwise, there is disagreement.

The second component contributing to the robustness metric assesses whether there is a significant change between the historical and future periods across most models. Specifically, these steps were taken to assess whether or not there is a significant change:

1. For each model, calculate the whether the change between epochs is significant:
    a. Calculate the historical mean value, $\mu_{historical}$, of an annual variable for the 30-year epoch spanning years 1976-2005.
    b. Calculate the future mean value, μ_{future}, of an annual variable for the 30-year epoch spanning years 2035-2064 for the mid-century or spanning years 2070-2099 for the end-century.
    c. Take the difference between the means, $\Delta = \mu_{future} - \mu_{historical}$
    d. Fit a linear model to the historical dataset.
    e. Detrend the historical data by calculating the residuals of the linear model.
    f. Calculate the standard deviation of the linearly detrended, annual historical data, $\sigma_{1yr.}$
    g. Calculate the variability threshold using the following formula: $\gamma = \sqrt{2/30} * 1.645 * \sigma_{1yr}$
2. If ≥66% of models conclude that $\Delta > \gamma$ (the change is greater than the variability threshold), the signal emerges from the historical variability. Otherwise, the signal does not emerge from the historical variability.

In cases where the models agreed on the sign of change, the tool can also provide the sign of change they agreed on. The categorizations of the robustness metric results are summarized in Table 13. The visualization of these different categories will be discussed in Section 3.3.

Table 13: Categorizations of Robustness Metric

Category	Sign of Change Agreement (≥80% of all models agree on sign of change)	Sign of Change	Robust Signal (≥66% of models show change greater than variability threshold γ)
Robust Signal, Positive	True	Positive	True
Robust Signal, Negative	True	Negative	True
Weak Signal, Positive	True	Positive	False
Weak Signal, Negative	True	Negative	False
Conflicting Signals	False	N/A	True
No Signal	False	N/A	False

The CHAT robustness metrics are derived from the IPCC's AR6 robustness categories with a few minor modifications to align with the USACE's use cases. The first difference is the epoch lengths. The IPCC uses 20-year epochs for the historical, mid-century, and end-century periods. In CHAT v2.2, 30-year epochs have been used for the mid-century and end-century and a 56-year epoch has been used for the historical period for epoch-based changes between the historical and future periods (represented by boxplots). In CHAT v2.3, the historical period used for the epoch-based changes has been shortened to the last 30 years within the historical period (years 1976-2005) to be consistent with the epoch length used for the future epochs. For the robustness metrics in CHAT v2.3, 30-year epochs are used for the historical, mid-century, and end-century periods. There is precedent to use 30-year epochs when analyzing the LOCA-downscaled data used in CHAT (https://scenarios.globalchange.gov/loca-viewer/). Additionally, streamflow tends to change at a slower rate than other variables, so a 30-year epoch is more likely to pick up on a trend. The change in epoch length is reflected in the variability threshold formula. The formula used in the IPCC report is

$$\gamma = \sqrt{\frac{2}{20}} * 1.645 * \sigma_{1yr},$$

whereas the formula used in CHAT is

$$\gamma = \sqrt{\frac{2}{30}} * 1.645 * \sigma_{1yr}.$$

The other change from the IPCC report's robustness metric definitions is the categorization. In the IPCC report, there are three categories of the robustness metric: 1) Robust Signal, 2) No Change or No Robust Signal, and 3) Conflicting Signals. These categories do not account for the sign of change. Additionally, the IPCC's "No Change or No Robust Signal" category combines both the "No Robust Signal" (positive or negative) and the "No Robust Signal, No Agreement on Direction of Change" categories. CHAT v2.3 expands the IPCC report's categories to provide the user with all relevant information.

Note that the *Modeled Time Series Trend Analysis* tab and the robustness metric results displayed in the *Modeled Time Series Explorer* tab are different. Trend analysis assesses whether the slope of the *inter-model mean* is statistically significant (i.e., different enough from zero, p-value<0.05) for the full historical (1951-2005) and projected (2006-2099) periods of analyses. The robustness metric assesses if most GCM based outputs agree that the difference between the historical and future epoch means (1) changes in the same direction, and (2) is significantly larger than the historical variability. Due to these differences, these analyses' results may conflict in the objective identification of changes. For example, the trend analysis may identify a significant trend, but the signal may not be robust because the difference is not appreciably larger than the variability exhibited throughout the historical simulation period.

2.3. Constraints and Limitations

The CHAT relies on meteorologic model outputs produced using GCMs and streamflow values generated using the VIC hydrologic model. Assumptions are inherent to any modeling process. Modeling assumptions constrain how outputs can be used in subsequent analysis. The existing constraints to applying and interpreting the values presented in the CHAT are as follows:

1. Future projections start in 2006. When CMIP5 was developed, 2006 was the cutoff year where GCM simulations began to use projections of emissions, rather than a reconstruction of historical greenhouse gas emissions, as boundary conditions.
2. Time series plots are only available starting in water year 1951. The source model outputs start on January 1, 1950, whereas the water year 1950 spans from October 1, 1949, to September 30, 1950. Note: Water year 2006 is part of the future time frame, but in this tool, it is a hybrid value rather than a pure future projection. Model outputs from both the last three months of the historical simulation timeframe (October 1, 2005–December 31, 2005) and the first nine months of the future simulation timeframe (January 1, 2006–September 30, 2006) were used to calculate the complete 2006 water year (October 1, 2005–September 30, 2006).
3. Do not use the simulated trendlines in the ***Modeled Time Series Trend Analysis*** tab to predict exact changes in future hydrologic variables. Numerical results represented in the tool should not directly support any USACE study/analysis.
4. Simulated historical model outputs for water years 1951–2005 should not be treated the same as observed historical data. Similarly, projected model outputs for water years 2006–present should not be compared directly to observed data. Analyzing both observed and modeled trends is important. However, for the historical trends, do not evaluate direct comparisons between the observed and modeled trends. Note: The agreement in the trends between model output and observations supports the potential for increased likelihood of climate impacts, but trend disagreement does not need to be diagnosed. Disagreement between simulated historical model output and observations had two primary causes:
    a. The modeled trend is a mean of output derived from an ensemble of GCMs. Each GCM has its own unique sequence of weather events and climate variability over the historical period, which is different than what was observed.
    b. The hydrologic models used to model climate-changed influence response often represent different conditions from the historical observations (e.g., static land surface, different drainage areas, no effects of river regulation or withdrawals).
5. The VIC model is configured to model the unregulated flow response. The results presented within the CHAT do not account for the impact of existing hydraulic structures on streamflow.
6. The mizuRoute scheme to route the runoff into a network of stream segments does not account for man-made regulation or the effects of man-made structures like levees. Therefore, the simulated routed runoff output displayed in the CHAT may not reflect reality in some cases. For example, by not accounting for levee overtopping, and constraining simulated streamflow to being representative of channelized flow, attenuation is not accurately accounted for.
7. Even for unregulated watersheds (i.e., those without man-made hydraulic infrastructure), VIC outputs are not directly comparable to observed flow data. This is due to several factors:
    a. The location-specific implications (or lack thereof) of VIC model calibration (see #8, below).
    b. The observed record is limited to events that have occurred, whereas modeled time series contain many more events and more variability.

c. GCMs capture larger-scale weather and climate features, not local effects.

d. Downscaling translates to regional and local scales, but GCM artifacts can still persist.

8. Generally, calibrations of VIC model applications for basins and streamflow locations (e.g., Colorado River at Imperial Dam or Feather River at Oroville) uniformly modified several model variables (e.g., infiltration rate). The calibration used relationships between observed hydrologic response and the physical properties of the watersheds being modeled or used calibrated parameters from previous regional studies involving more in-depth model calibration. Thus, the VIC model has only been coarsely calibrated across the CONUS. Calibration quality varies depending on the physical process that dominates runoff response and locale. Model calibration also depends on the availability and accuracy of hydrological observations, both in terms of using the observed meteorologic data to downscale the GCM outputs and using the observed streamflow data for model calibration.

9. All model simulations of streamflow contain error, which is commonly reduced (but not eliminated) through model calibration (parameter estimation). However, even where the model is adequately calibrated to historical climate and weather conditions, in simulating future change, the hydrologic model may be required to represent conditions that lie beyond what it has experienced in the historical record, with unknown impacts on its ability to simulate such conditions. If the model has realistic sensitivities in historical climate (e.g., its simulation of the change in runoff in response to precipitation and temperature change), it may indicate that the model is reliable at extrapolating beyond historical conditions.

10. The lack of a comprehensive model calibration is in part due to the non-availability of naturalized streamflow records in many parts of the country, as well as the longstanding scientific challenge of regional parameter estimation for land models in ungauged basins.

11. The annual max monthly mean routed runoff variable is not directly equivalent to "peak flow," and therefore, one should be cautious in interpreting simulated trends in this variable. For smaller basins or snowmelt-dominated basin annual peaks, streamflow for short durations may not correlate well with annual maximum monthly mean flow. The simulated trend in the annual maximum of the monthly mean streamflow represents the trend in a monthly volume of streamflow, which means that it does not represent the actual peak daily streamflow. Peak flows could exhibit a different behavior over time. For example, in snowmelt-dominated regions, where bulk monthly volumes may be decreasing, peak volumes at shorter durations could be increasing or remaining stable. Therefore, apply caution when comparing the CHAT streamflow variables to other resources; for example, historical peak streamflow observation (e.g., from USGS) or modeled flood risk projections in mountainous regions.

12. The one-day duration precipitation metrics derived from LOCA-downscaled GCM outputs can have a low bias. Statistical downscaling techniques use gridded historical observations to downscale and bias-correct the coarser scale GCM products. The observational dataset for LOCA (Livneh et al., 2013) has known issues in representing daily precipitation intensities. These issues are attributed to the way the dataset incorporates station data. Weather station data undergoes a time-of-day correction which for some regions results in a low bias of 24-hour precipitation intensity (Risser et al., 2021). This low bias of 24-hour precipitation

intensity propagates through LOCA-downscaled products based on the Livneh et al. observational dataset.

13. Other factors can also undermine the quality of the historical and projected forcings:
    a. Errors in the meteorological forcings used to drive the historical model;
    b. Errors in deriving bias-corrected projected forcings, whether random or from systematic issues such as gauge under catch; or
    c. Uncertain estimation in areas of sparse meteorological observations.

3. CHAT Application

Users can view the inter-model, inter-scenario statistics of simulated historical and future hydrologic and meteorologic variables for each eight-digit HUC basin in the CONUS. Additionally, users can view streamflow variables on a stream segment basis. See the Data Sources and Processing Methodologies sections for detailed description of the climate model outputs (e.g., where the outputs are generated and the methodology by which they were produced) and the metrics displayed in the CHAT. Please refer to the Constraints and Limitations section for guidance on interpretation of the information displayed in the CHAT.

The CHAT contains seven tabs, as shown in Figure 1:
1. Home
2. Study Location Selector
3. Modeled Time Series Explorer
4. Modeled Time Series Trend Analysis
5. Monthly Box Plots: Epoch-Based Changes
6. Annual Box Plots: Epoch-Based Changes
7. Help.

| Home | Study Location Selector | Modeled Time Series Explorer | Modeled Time Series Trend Analysis | Monthly Box Plots: Epoch-Based Changes | Annual Box Plots: Epoch-Based Changes | Help |

Figure 1: Tabs at the Top of the CHAT Page

The following sections discuss the contents of each CHAT tab.

3.1. Homepage Explorer

When the CHAT first loads, users are directed to the *Home* tab, shown in Figure 2, and are presented with information about the tool and a button to get started exploring the tool.

Figure 2: Home Tab

3.1.1. Overview

The top of the ***Home*** tab has a section titled "What's in the CHAT" that provides a summary of the data found in the tool on subsequent tabs. Additionally, the ***Get Started on Study Location Selector Tab!*** Button takes the user the ***Study Location*** tab.

Below this top section are collapsible boxes containing additional context related to the CHAT (e.g., output displayed, variables included). Information about why CHAT was developed is provided in the ***Tool Introduction & Motivation*** section. A comprehensive list of the variables available in the tool is given in the ***CHAT Variables Available for Analysis*** section. The latest tool updates are summarized in the ***Tool Updates*** section. Details on the metadata related to how the metrics in the tool are generated from climate model outputs are provided in the ***Model Output Methodology*** section.

To begin exploring the tool, the user can press the ***Get Started on Study Location Selector Tab!*** button (#1 in
Figure 2).

3.2. Study Location Selector

To the right of the ***Home*** tab is the ***Study Location Selector*** tab. This tab can be accessed in two ways: by clicking on the ***Get Started on Study Location Selector Tab!*** button on the ***Home*** tab or by clicking on the tab name itself.

This tab presents users with a map of the 2- and 4-digit HUC basins in the CONUS (Figure 3). A 4-digit HUC basin must first be selected to display the 8-digit HUC basin boundaries. As indicated previously, HUC basins along the U.S. borders with Mexico and Canada are truncated at the international border; this is apparent when basins are visualized within the *Study Location Selector* tab. Once an 8-digit HUC is selected, the HUC's terminal stream segment is selected by default. To view data on the 8-digit HUC level (as provided in CHAT v2.2), the terminal stream segment should be selected. Otherwise, to view streamflow variables for a specific stream segment, the user can select their desired stream segment within the 8-digit HUC. On subsequent tabs, streamflow variables are shown for the selected stream segment and precipitation and temperature variables are shown for the corresponding 8-digit HUC.
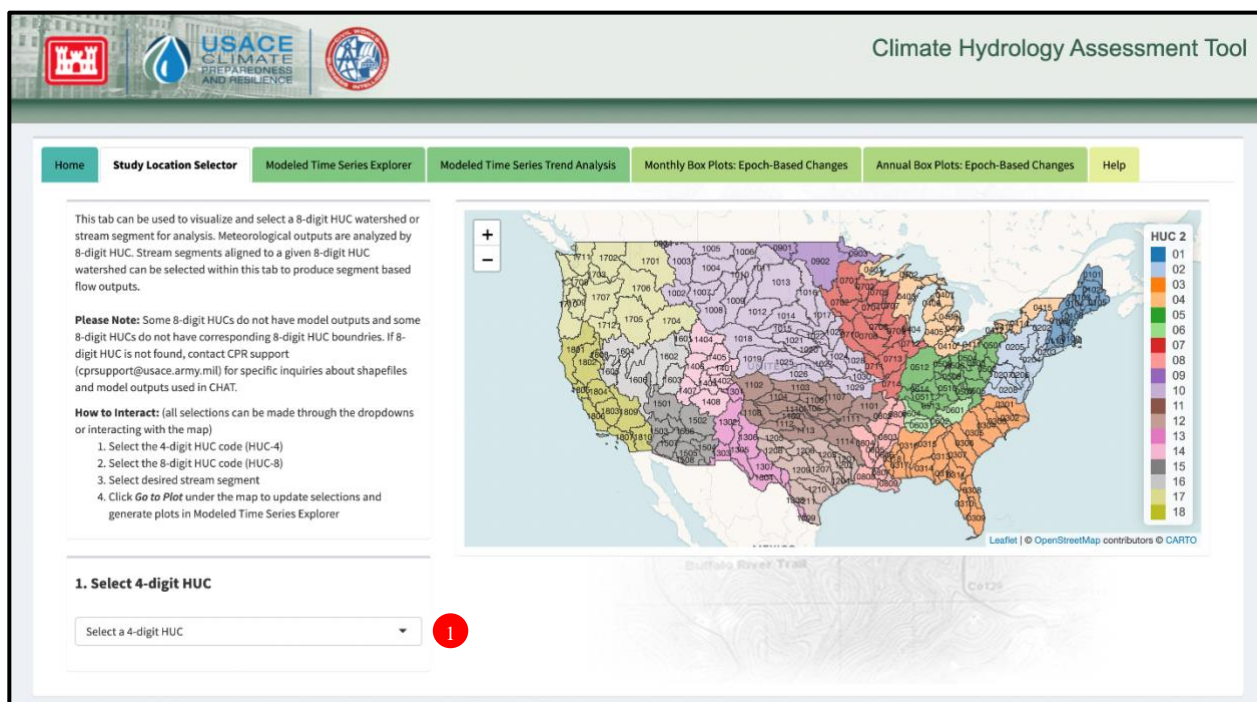
Figure 3: Study Location Selector Tab and 4-Digit HUC Basin Selection

3.2.1. Overview

Three drop-down menus can be applied to select the desired 8-digit HUC basin and stream segment for analysis. Alternatively, the user may select their desired study area by clicking directly on the map.

The first drop-down menu, *Select HUC-4,* selects the 4-digit HUC basin encompassing the study area (#1 in Figure 3). If the user clicks on the map to select the 4-digit HUC basin, the drop-down menu auto-populates with their selection. Once a 4-digit HUC basin is selected, the map zooms into that 4-digit HUC basin and displays the 8-digit HUC sub-basins that fall within the selected 4-digit HUC basin (Figure 4). The +/- buttons zoom in and out within a specific 4-digit HUC basin. Placing the cursor over the map and scrolling with a mouse also allows the user to zoom in and out. The user can then select an

8-digit HUC basin for analysis from the second drop-down menu, labeled *Select HUC-8* (#2 in Figure 4) or by clicking the desired 8-digit HUC on the map.

Figure 4: 8-Digit HUC Basin Selection for Selected 4-Digit HUC Basin

Some 8-digit HUC basins do not have model outputs, and some do not have corresponding boundaries. If an 8-digit HUC is not found on the *Study Location Selector* tab, contact CPR support (cprsupport@usace.army.mil) for specific inquiries about shapefiles and model outputs used in the CHAT.

Once an 8-digit HUC basin is selected, the tool auto-selects and zooms into the terminal stream segment for that 8-digit HUC basin and displays the upstream stream segments that fall within it. The terminal stream segment is colored red, and all other stream segments are colored blue. The stream segment currently selected is highlighted yellow.

For the total, cumulative streamflow exiting a given 8-digit HUC basin, use the default terminal stream segment. To analyze streamflow data at the stream segment level, select the stream segment of interest on the map or in the *Select Stream Segment* drop-down menu (#3 in Figure 5). In either case, the temperature and precipitation variables for the corresponding 8-digit HUC are displayed on subsequent tabs.

After the 8-digit HUC basin and stream segment of interest have been selected, click the *Submit Inputs* button (#4 in Figure 5) to navigate to the *Modeled Time Series Explorer* tab. Alternatively, to choose a different region than the one selected, click the *Reset Map* button (#5 in Figure 5) to reset the map to the 2- and 4-digit HUC basin view.
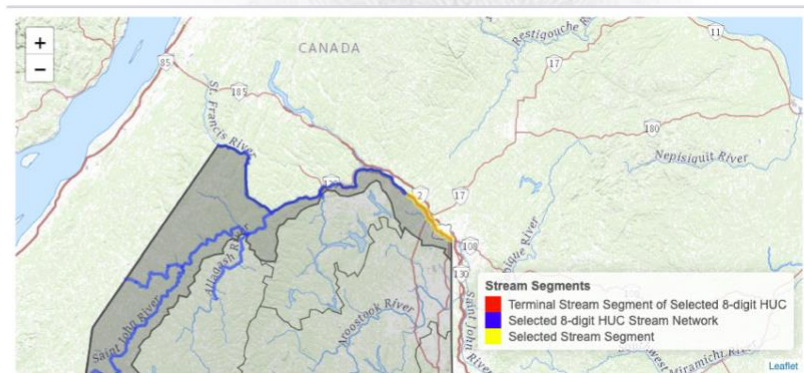
Figure 5: Stream Segment Selection for Selected 8-Digit HUC Basin

Once a stream segment is selected, a toggle labeled ***Flag Coastal Flood Risk*** appears (#6 in Figure 5). This functionality is enabled by default when the user first accesses the site but can be turned off for the remainder of a session if desired. When this functionality is enabled, the banner shown in Figure 6 appears to alert the user when a coastal stream segment poses a flood risk due to low elevation.

Figure 6: Coastal Flood Risk Banner

3.3. Modeled Time Series Explorer

To the right of the ***Study Location Selector*** tab is the ***Modeled Time Series Explorer*** tab. The banner at the top of the page displays the name of the 8-digit HUC basin and stream segment associated with the simulated output currently being displayed. The tab includes an ***About the CMIP5 Modeled Output*** section that describes the visualizations and the output being displayed.

3.3.1. Overview

The *Modeled Time Series Explorer* tab displays annual time series streamflow output for a given stream segment and annual time series precipitation and temperature outputs for the corresponding 8-digit HUC basin. The visualizations depict the range of modeled values across the 32 LOCA downscaled GCM-based simulations for the selected RCP(s). Outputs are displayed for water years 1951–2099. Robustness metrics can also be viewed in this tab.

3.3.2. Tab Contents and User Interface Features

The *Modeled Time Series Explorer* tab has three stacked figures showing streamflow, precipitation, and temperature output, respectively (Figure 7). These figures visualize the annual (water year based) time series of the user-selected hydrologic variables, as well as the spread in modeled variable values, allowing the user to conceptualize some of the uncertainty associated with the projected, climate-influenced conditions.

Two options are available for visualizing inter-model statistics of annual time series variables. One option plots the inter-model mean and range of the time series, where the bold line represents the inter-model (32 GCMs) mean of modeled variable values and the shaded area represents the inter-model (32 GCMs) range (the inter-model minimum to the inter-model maximum) of modeled variable values. The second option plots the 1st, 2nd, and 3rd quartiles (i.e., 25th percentile, median, and 75th percentile), where the bold line represents the inter-model median of modeled variable values, and the shaded area represents the inter-model inter-quartile range (1st quartile to 3rd quartile) of modeled variable values. The following color scheme differentiates between the historical period (1951–2005) and the future period (2006–2099) outputs and indicates the RCP assumptions being applied:

- The simulated historical outputs have a bold, black line and gray-shaded area.
- The simulated future values for the RCP 4.5 scenario have a bold, blue line and blue-shaded area.
- The simulated future values for the RCP 8.5 scenario have a bold, orange line and a yellow-shaded area.
- When the user selects both the RCP 4.5 and RCP 8.5 scenarios, both lines and shaded areas appear overlaid on the same plot.

The features of the user interface are described below and shown in Figure 7 by the corresponding numbers.

1. To navigate to a different stream segment or 8-digit HUC basin, click the ***Back to Study Location Selector*** button to return to the ***Study Location Selector*** tab.
2. Users can choose from a selection of modeled streamflow, temperature, and precipitation variables via the pull-down lists. Upon changing this section, also press the ***Reload Plot*** button to load the selected output.
3. Users can choose which inter-model statistics to display. The user can choose to view the mean and range of the outputs or the median and inter-quartile range of the outputs. Upon changing this section, also press the ***Reload Plot*** button to load the selected output.
4. Users can choose to display a single RCP scenario or both RCP scenarios for the streamflow, precipitation, and temperature outputs for the future timeframe. Upon changing this section, also press the ***Reload Plot*** button to load the selected output.
5. Users can choose to display streamflow, precipitation, and temperature outputs in either U.S. customary units or metric units. The tool defaults to displaying customary units. Upon changing this section, press the ***Reload Plot*** button to load the selected output.

6. If a single RCP scenario is selected, the user can choose to display the robustness metrics calculated for that scenario for the mid- and end-century epochs by checking the ***Show Robustness Metrics*** box. Note: This option is not available when both RCPs are displayed. Upon changing this section, also press the ***Reload Plot*** button to load the selected option.

7. By clicking on the circled icon (i.e., three stacked horizontal bars) in the upper right-hand corner of each plot, users can view the plots in full screen or download the graphics as PNG, JPEG, PDF, or SVG files.
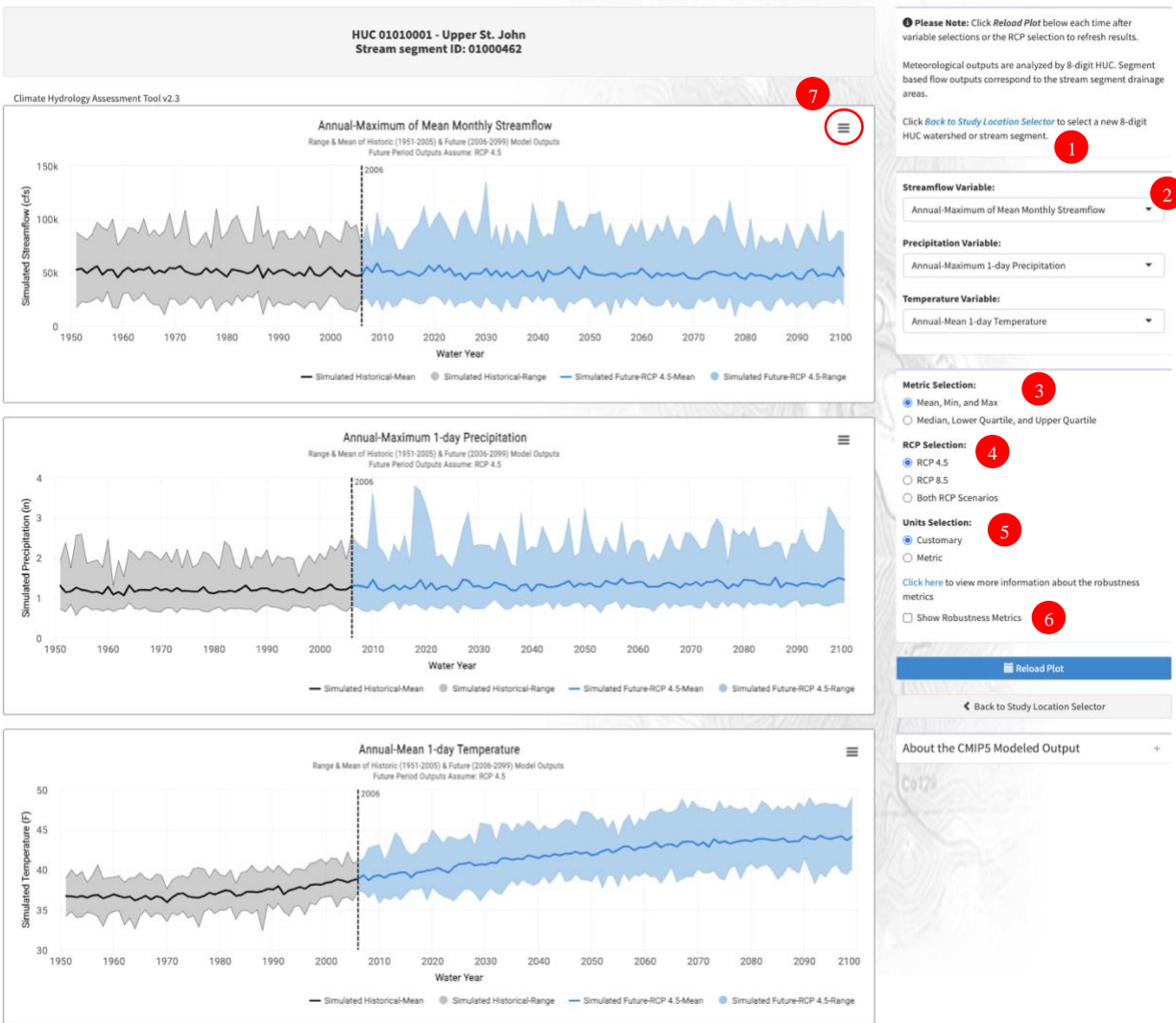
Figure 7: Modeled Time Series Explorer Tab

When the ***Show Robustness Metrics*** box is checked, the legend for the robustness metrics appears (#1 in Figure 8). After the ***Reload Plot*** button is pressed, patterned and colored overlays appear spanning the mid-century epoch (i.e., water years 2035–2064) and the end-century epoch (i.e., water years 2070–2099)

per each plot (i.e., for streamflow, precipitation, and temperature variables). The legend determines the robustness metrics that correspond to the patterned and colored overlays on each plot.
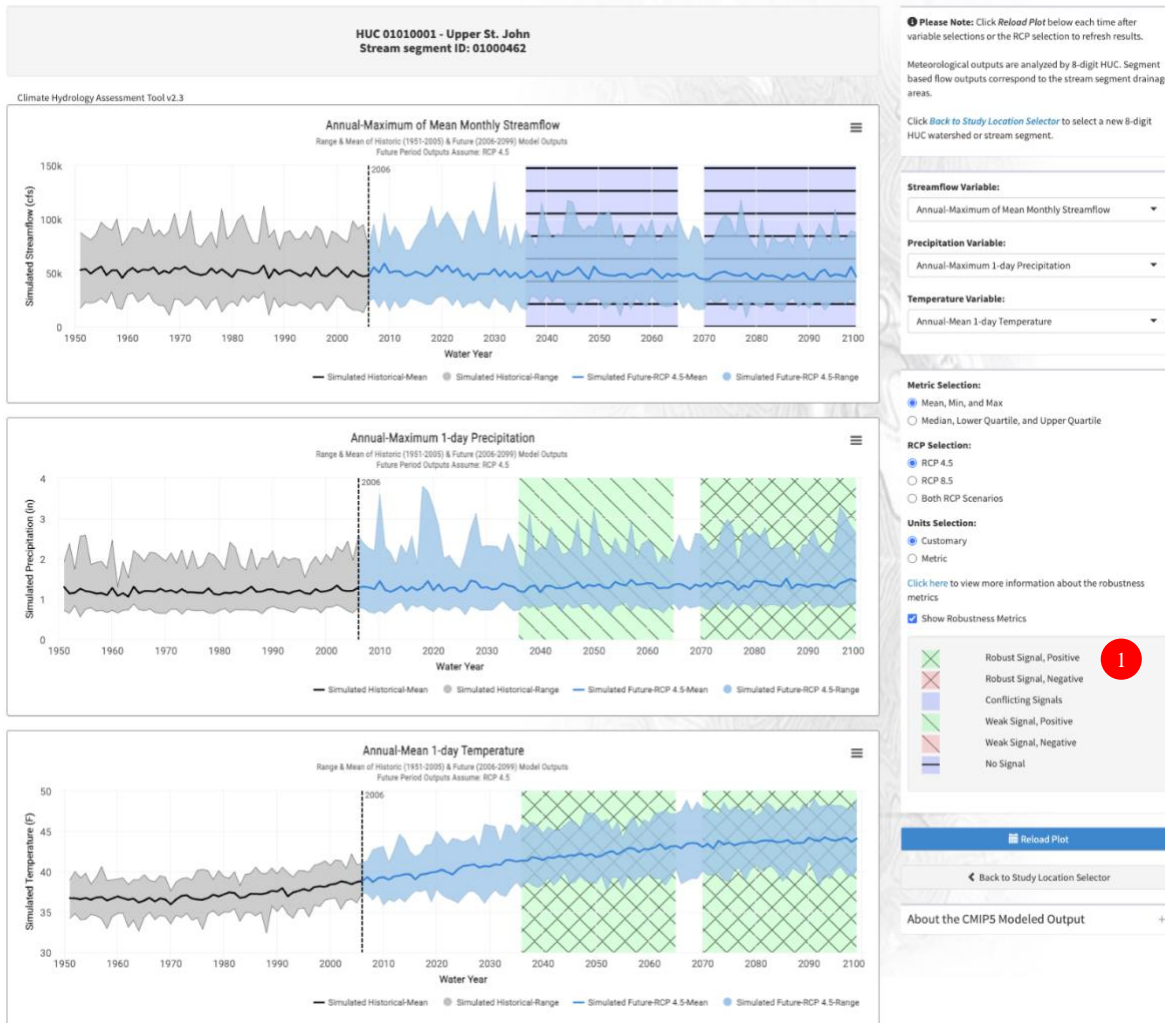
Figure 8: Modeled Time Series Explorer Tab with Robustness Metrics Shown

3.3.3. Interpretation

This tab enables users to visualize simulated, annually aggregated, streamflow, precipitation, and temperature outputs for both the historical and future periods. The figures enable the user to conceptualize the inter-model range of simulated hydrology for the selected stream segment and corresponding 8-digit HUC basin. As described in Section 2.1, the ranges of modeled output reflect the assumptions and uncertainty inherent to the various aspects of the modeling chain that produce the outputs displayed in the CHAT (i.e., GCM configurations, GCM boundary conditions, RCPs, LOCA downscaling method, and VIC modeling method).

This tab reports robustness metrics per scenario-epoch combination as an optional overlay, in addition to a set of three metrics which can include the first set:
1. The inter-model minimum (the lower boundary of the shaded area)
2. The inter-model maximum (the upper boundary of the shaded area)
3. The inter-model mean (the bold center line)

or the second set:
1. The inter-model first quartile (the lower boundary of the shaded area)
2. The inter-model third quartile (the upper boundary of the shaded area)
3. The inter-model median (the bold center line).

Users can gain insight into how well-constrained (and therefore how uncertain) the simulated variable values are by examining the range of simulated variable values. Further, users can quickly gain a sense for the range of possible future hydrologic conditions. This tab makes allows users to incorporate simulated climate change uncertainty into their risk analysis.

The year-to-year changes in the mean of the projected simulations are not indicative of what can be anticipated in the future (i.e., one should not expect that an increase in a given variable from one year to the next will occur). Rather, results should be considered in terms of broader changes over longer timespans. In addition, results should always be considered holistically. Projections of future conditions based on one or a small subset of GCMs do not adequately capture the uncertainty inherent to evaluations of climate-influenced hydrology.

For more information on the calculations performed to derive the simulated variable values and the inter-model statistics for those variables, refer to Section 2.2.

In addition to visualizing the inter-model mean and range, this tab also provides robustness metrics, which provide insight into the inter-model robustness of a variable's future trend. The robustness metrics assess whether most GCM-based projections agree on the direction of the future trend and whether most GCM-based projections agree that the future trend emerges from the simulated historical variability. For further details on how these robustness metrics are derived, see Section 2.2.4.

3.4. Modeled Time Series Trend Analysis

The *Modeled Time Series Trend Analysis* tab shows a trend analysis of the mean across the GCM-based simulations for a selected variable. The tab includes an *About the CMIP5 Modeled Output* section which describes the visualizations and the output being displayed. Below the *About the CMIP5 Modeled Output* section, a description of *p-value Guidance* describing how to interpret the p-values associated with all the statistical tests applied is included.

3.4.1. Overview

In the *Modeled Time Series Trend Analysis* tab, linear regression models are separately fitted to simulated historical and future time series. Modeled slope and three tests for monotonic trends are calculated for each of the two subsets of GCM-based outputs (i.e., water years 1951–2005 and water years 2006–2099). The simulated historical and future trends presented within the CHAT can be compared to give insight to future climate change impacts. The trendlines for simulated historical and

future period outputs are not continuous because the trendlines are calculated separately for the two subsets of outputs.

In all figures, the following color schemes are applied to differentiate between the historical period (1951–2005) and the future period (2006–2099) output and to indicate what RCP assumptions are being applied:

- The inter-model mean of simulated historical variable values for water years 1951–2005 is denoted by a solid gray line.
- The trendline in the mean of the selected variable for the simulated historical period (water years 1951–2005) produced using linear regression is denoted by a dashed black line.
- The inter-model mean of the selected variable for the future period (water years 2006–2099) is denoted by a solid light blue line.
- The trendline in the mean of the selected variable for the future period (water years 2006–2099) produced using linear regression is denoted by a dashed dark-blue line.

3.4.2. Tab Contents and User Interface Features

The content displayed within the *Modeled Time Series Trend Analysis* tab and key features of the user interface are described below and shown in Figure 9.

1. If a user would like to navigate to a different stream segment or 8-digit HUC basin, they can click the *Back to Study Location Selector* button to be taken back to the *Study Location Selector* tab.
2. Users can choose from a selection of modeled streamflow, precipitation, and temperature variables via the *Select Variable* drop-down menu. Upon changing the selected variable, the user must press the *Reload Plot* button to refresh the results.
3. Users can select which RCP scenarios to display for the future timeframe. Upon changing this section, the user must also press the *Reload Plot* button to load the selected output.
4. Users can choose to display streamflow, precipitation, and temperature outputs in either customary or metric units. The tool defaults to displaying customary units. Upon changing this section, the user must press the *Reload Plot* button to load the selected output.
5. By clicking on the circled icon (i.e., three stacked horizontal bars) in the upper right-hand corner of each plot, users can view the plots in full screen or download the graphics as PNG, JPEG, PDF, or SVG files.
6. The linear regression trendline slope for the historical simulation period (water years 1951–2005) and future simulation period (water years 2006–2099) are displayed directly under the plot. The slope of the linear regression trendline provides insight into both the directionality and the magnitude of simulated change over the historical and future periods.
7. The p-values associated with three tests for the presence of monotonic trends (Student's t-test, Mann-Kendall, and Spearman Rank-Order) are displayed at the bottom of the tab for both the simulated, historic, and future periods.
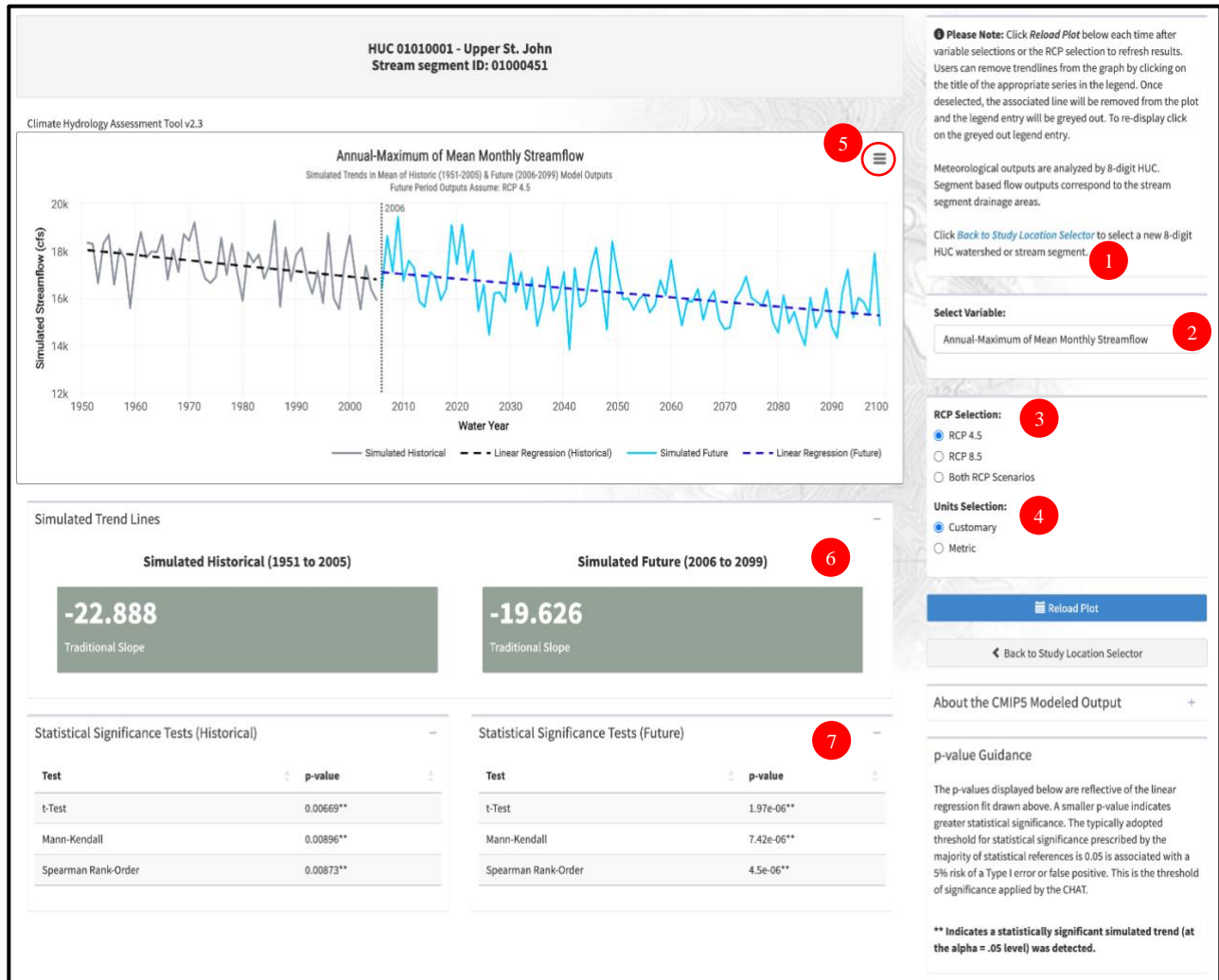
Figure 9: Modeled Time Series Trend Analysis Tab

3.4.3. Interpretation

The *Modeled Time Series Trend Analysis* tab enables the user to compare the directionality (slope) and significance of trends (p-values) in simulated historical and future outputs generated using the same meteorologic and hydrologic modeling platforms and downscaling techniques. Differences can provide insight into foreseeable changes to basin hydrology due to climate change. For more information related to statistical tests applied and metrics used to define statistical significance please refer to Section 2.2.3. Potential results and suggested interpretation are listed in Table 14. It is important to recognize that although there may be significant trends in the inter-model mean values of simulated outputs, there is considerable uncertainty associated with these trends as a result of the wide range of future, hydrologic conditions projected by the suite of GCMs.

Table 14: Suggested Interpretation of Trend Analysis Results

Trend Analysis: Simulated Mean		Examples of Interpretation
Historical Period	**Future Period**	
p-value (5% significance level)		
Significant	Significant	If the directionality of the trends in simulated historical values is different than the directionality of the trend associated with the projected values, it is reasonable to conclude that climate change may cause a shift in future conditions in the study area relative to conditions observed in the past. If the directionality of the trends is the same, it may be that changes in hydrologic conditions influenced by climate change are already materializing in the region and can be anticipated to persist into the future.
Significant	Non-significant	Because no statistically significant trends are detected in future variable values, no conclusions about future climate change impacts can be made based on the CHAT output. The trend in simulated historical variable values should be discussed, but its implications with respect to climate change are uncertain.
Non-significant	Significant	The statistically significant change in simulated future values contrasting with the lack of trend in the simulated historical values suggests that conditions will change in the future due to climate change.
Non-significant	Non-significant	If there is no statistically significant trend detected in either the simulated historical or future values, no conclusions related to climate change impacts can be made based on the CHAT output.

The magnitude of the trend's rate of change can be evaluated in addition to its significance based on the slope computed for the linear regression equation. It is possible to get significant trends for miniscule changes in time series with low variance. The best way to assess the slope's magnitude is to evaluate changes in the mean of the variable being analyzed in terms of percent change per fifty years or percent change per century. That way the interpretation is easier: The simulated multi-model mean is projected to change by a given percentage over a given amount of time. A significant trend with a relatively small slope (perhaps <0.5%/decade) could lead the interpreter to conclude that climate change is not likely to cause an operationally significant shift in the magnitude of the variable being analyzed.

3.5. Monthly Box Plots: Epoch-Based Changes

The fourth tab from the left is the ***Monthly Box Plots: Epoch-Based Changes*** tab. The banner at the top of the page displays the name of the 8-digit HUC basin and the stream segment associated with the output currently being displayed. This tab displays modeled monthly epoch-based changes for hydrological variables for a selected stream segment and meteorological variables for the corresponding 8-digit HUC basin. Monthly epoch-based changes represent the difference in historical and future epoch-means for each RCP resolved of the 32 GCM-based outputs on a monthly scale. The tab includes an ***About the CMIP5 Modeled Output*** section which describes the visualizations and the output being displayed.

3.5.1. Overview

The purpose of the ***Monthly Box Plots: Epoch-Based Changes*** tab is to allow the user to visualize simulated changes in monthly streamflow, precipitation, and temperature over time. Output is displayed using a series of box plots. These visualizations depict the range of epoch-based changes in modeled variable values across the 32 GCM-based simulations per RCP presented within the CHAT.

For each month, box plots are displayed side-by-side for both future RCP scenarios. This allows users to understand the differences in the magnitude of changes that result from applying different RCP assumptions. In all figures, the following color scheme is applied to indicate what RCP assumptions are being applied:

- The red box-and-whisker plots represent the change from simulated historical (Base epoch) to future (Mid-Century epoch or End-Century epoch) for the RCP 4.5 scenario.
- The blue box-and-whisker plots represent the change from simulated historical (Base epoch) to future (Mid-Century epoch or End-Century epoch) for the RCP 8.5 scenario.

3.5.2. Tab Contents and User Interface Features

As shown in Figure 10, there are three stacked figures displayed in the ***Monthly Box Plots: Epoch-Based Changes*** tab. The top figure shows the results associated with a modeled streamflow variable, the middle figure shows the results for a modeled precipitation variable, and the bottom figure shows the results for a modeled temperature variable. These figures depict the simulated change in the epoch-mean monthly values between two time periods or epochs. The term "epoch-mean" is defined as the mean of the monthly variable values across all years within an epoch for the selected RCP, calculated per each of the 32 different GCM outputs. Each figure is separated into two sub-plots arranged horizontally; these sub-plots display the simulated, epoch-based changes from the Base epoch (water years 1976–2005) to the Mid-Century epoch (water years 2035–2064) on the left and from the Base epoch to the End-Century epoch (water years 2070–2099) on the right. How the simulated, epoch-based changes are calculated is described in detail in Section 2.2.

The features of the user interface are described below, as well as shown in Figure 10.
1. If a user would like to navigate to a different stream segment or 8-digit HUC basin, they can click the ***Back to Study Location Selector*** button to be taken back to the ***Study Location Selector*** tab.
2. Users can choose from a selection of modeled variables via the ***Streamflow Variables, Precipitation Variables,*** and ***Temperature Variables*** drop-down lists. Upon changing the selected variables, the user must press the ***Reload Plot*** button to refresh the results.

3. For the precipitation variables, epoch-based changes ("Value") and percent changes ("Percent Difference") are both available. The user can toggle between these options using the radio dials. Upon changing the selected value, the user must press the ***Reload Plot*** button to refresh the results.

4. Users can choose to display streamflow, precipitation, and temperature outputs in either customary or metric units. The tool defaults to displaying customary units. Upon changing this section, the user must press the ***Reload Plot*** button to load the selected output.

5. By clicking on the circled icon (i.e., three stacked horizontal bars) in the upper right-hand corner of each plot, users can view the plots in full screen or download the graphics as PNG, JPEG, PDF, or SVG files.

Figure 10: Monthly Box Plots: Epoch-Based Changes Tab

The median and the inter-model spread of the simulated, epoch-mean changes (or percent changes) is conveyed using box-and-whisker plots. This allows the user to conceptualize some of the uncertainty associated with the projected, climate-influenced conditions. The five elements of the box-and-whisker plots (i.e., "box plots") described below and shown in Figure 11 represent common statistical properties used to characterize data.

1. The **center bold line** represents the inter-model **median** of the variable values.
2. The **bottom edge of the box** represents the **1st quartile** ($q_{0.25}$) of the inter-model variable values. The 1st quartile is defined as the value below which 25% of the variable values reside.
3. The **top edge of the box** represents the **3rd quartile** ($q_{0.75}$) of the inter-model variable values. The 3rd quartile is defined as the value below which 75% of the variable values reside.
4. The **bottom whisker (aka "fence")** represents the **outlier-independent minimum** of the inter-model variable values.
5. The **top whisker (aka "fence")** represents the **outlier-independent maximum** of the inter-model variable values.

Simulated variable values for some models are not displayed in the box-and-whisker plot range because they have been classified as "**outliers**" using the interquartile range (IQR) criterion based on the simulated variable values for all models. The IQR criterion means that all observations above $q_{0.75} + 1.5 *$ IQR or below $q_{0.25} - 1.5 *$ IQR (where, $q_{0.25}$ and $q_{0.75}$ correspond to the first and third quartile respectively, and IQR is the difference between the third and first quartile) are considered as potential outliers. In other words, all model outputs outside of the following interval are treated as outliers: I = $[q_{0.25} - 1.5 *$ IQR, $q_{0.75} + 1.5 *$ IQR]. In this context, "outliers" is a statistical term and does not necessarily have any bearing on the value or accuracy of the values that have been classified as outliers. Specifically, outliers should not be interpreted as unreliable or erroneous, but rather interpreted simply as statistically furthest from most of the other model values.
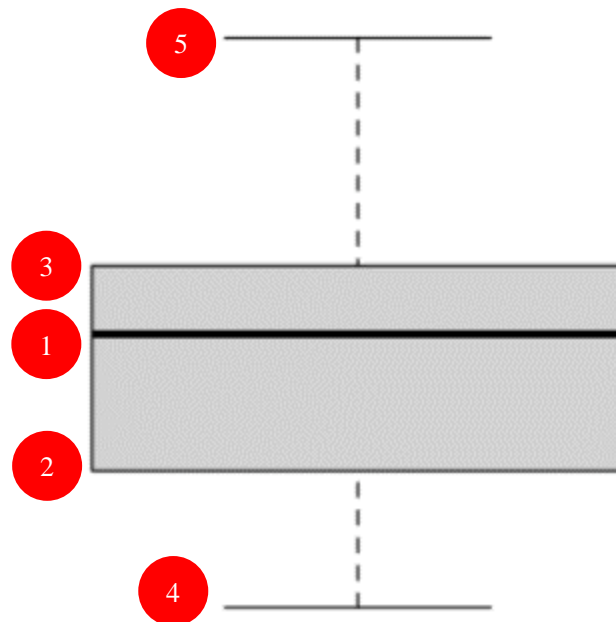

Figure 11: Box-and-Whisker Plot

3.5.3. Interpretation

This tab enables users to visualize simulated changes in streamflow, precipitation, and temperature at a monthly resolution between two epochs of time. The sign of the simulated, epoch-based change corresponds to the directionality of the change. For example, if epoch-based changes in simulated maximum temperature are mostly positive across each month, this indicates that the maximum temperature in that 8-digit HUC basin is likely to increase into the future. Conversely, if epoch-based changes in simulated maximum temperature are mostly negative across each month, this indicates that maximum temperature is likely to decrease into the future.

By displaying simulated, epoch-based changes for each month, users gain insight into how conditions change seasonally throughout the year. The directionality or magnitude of simulated change may vary depending on the time of the year. For example, the difference between the epoch-based mean of the simulated, monthly, accumulated precipitation may be projected to decrease or remain unchanged from the Base epoch to the mid-Century or end-Century epochs for the summer months, but it could be projected to increase in the spring months. Differences in how climate change impacts materialize throughout the year can be driven by seasonal patterns specific to a given region, for example, how snowmelt impacts an 8-digit HUC basin. How seasonal changes in temperature and precipitation patterns translate to shifts in streamflow response is not always readily apparent and varies considerably by region and basin.

The box-and-whisker markers capture the range of simulated changes generated by the suite of 32 GCMs. Half of the outputs defined based on the GCM results models span between the upper and lower horizontal lines of the box portion of the box-and-whisker plots. Excluding statistically defined outliers, the rest of the calculated outputs fall within the whiskers (aka "fences") representing the range of results derived from the 32 different GCMs. As described in Section 2.1, the spread of the calculated output reflects the uncertainty inherent to the modeling chain and assumptions applied to generate GCM-based simulations of temperature, precipitation and streamflow. As a result of this uncertainty, the median monthly changes between the Base epoch and a future epoch should not be interpreted as precise predictions of future conditions.

By examining the range of simulated outputs, users can gain insight into how well-constrained (and therefore how uncertain) the changes in the simulated variable are. For example, box-and-whisker markers with a larger range (interval between whiskers/fences) relative to other months or scenarios exhibit greater inter-model variability in the simulated variable changes, while box-and-whisker markers with a smaller range relative to other months or scenarios exhibit smaller inter-model variability (and therefore more agreement amongst GCMs) in the simulated variable changes.

3.6. Annual Box Plots: Epoch-Based Changes

The fifth tab from the left is the *Annual Box Plots: Epoch-Based Changes* tab. The banner at the top of the page displays the name of the 8-digit HUC basin and the stream segment associated with the output currently being displayed. This tab displays modeled annual epoch-based changes for streamflow variables for a selected stream segment and meteorological variables for the corresponding 8-digit HUC basin. Annual epoch-based changes represent the difference in historical and future epoch-means for each

RCP produced from the 32 GCM-based outputs on an annual scale. The tab includes an *About the CMIP5 Modeled Output* section which describes the visualizations and the output being displayed.

3.6.1. Overview

The purpose of the *Annual Box Plots: Epoch-Based Changes* tab is to allow the user to visualize simulated changes in annual streamflow, precipitation, and temperature over time. Output is displayed using a series of box plots. These visualizations depict the range of epoch-based changes in modeled variable values across the 32 GCM-based simulations per RCP presented within the CHAT.

Box plots are displayed side-by-side for both future RCP scenarios. This allows users to understand the differences in the magnitude of changes that result from applying different RCP assumptions. In all figures, the following color scheme is applied to indicate what RCP assumptions are being applied:

- The red box-and-whisker plots represent the change from simulated historical (Base epoch) to future (Mid-Century epoch or End-Century epoch) for the RCP 4.5 scenario.
- The blue box-and-whisker plots represent the change from simulated historical (Base epoch) to future (Mid-Century epoch or End-Century epoch) for the RCP 8.5 scenario.

3.6.2. Tab Contents and User Interface Features

As shown in Figure 12, there are three stacked figures displayed in the *Annual Box Plots: Epoch-Based Changes* tab. The top figure shows the results associated with a modeled streamflow variable, the middle figure shows the results for a modeled precipitation variable, and the bottom figure shows the results for a modeled temperature variable. These figures depict the simulated change in the epoch-mean annual values between two time periods or epochs. Each figure is separated into two sub-plots arranged horizontally; these sub-plots display the simulated, epoch-based changes from the Base epoch (water years 1976–2005) to the Mid-Century epoch (water years 2035–2064) on the left and from the Base epoch to the End-Century epoch (water years 2070–2099) on the right. How the simulated, epoch-based changes are calculated is described in detail in Section 2.2.

The features of the user interface are described below, as well as shown in Figure 12.
1. If a user would like to navigate to a different stream segment or 8-digit HUC basin, they can click the *Back to Study Location Selector* button to be taken back to the *Study Location Selector* tab.
2. Users can choose from a selection of modeled variables via the *Streamflow Variables, Precipitation Variables,* and *Temperature Variables* drop-down lists. Upon changing the selected variables, the user must press the *Reload Plot* button to refresh the results.
3. For the precipitation variables, epoch-based changes ("Value") and percent changes ("Percent Difference") are both available. The user can toggle between these options using the radio dials. Upon changing the selected value, the user must press the *Reload Plot* button to refresh the results.
4. Users can choose to display streamflow, precipitation, and temperature outputs in either customary or metric units. The tool defaults to displaying customary units. Upon changing this section, the user must press the *Reload Plot* button to load the selected output.
5. By clicking on the circled icon (i.e., three stacked horizontal bars) in the upper right-hand corner of each plot, users can view the plots in full screen or download the graphics as PNG, JPEG, PDF, or SVG files.

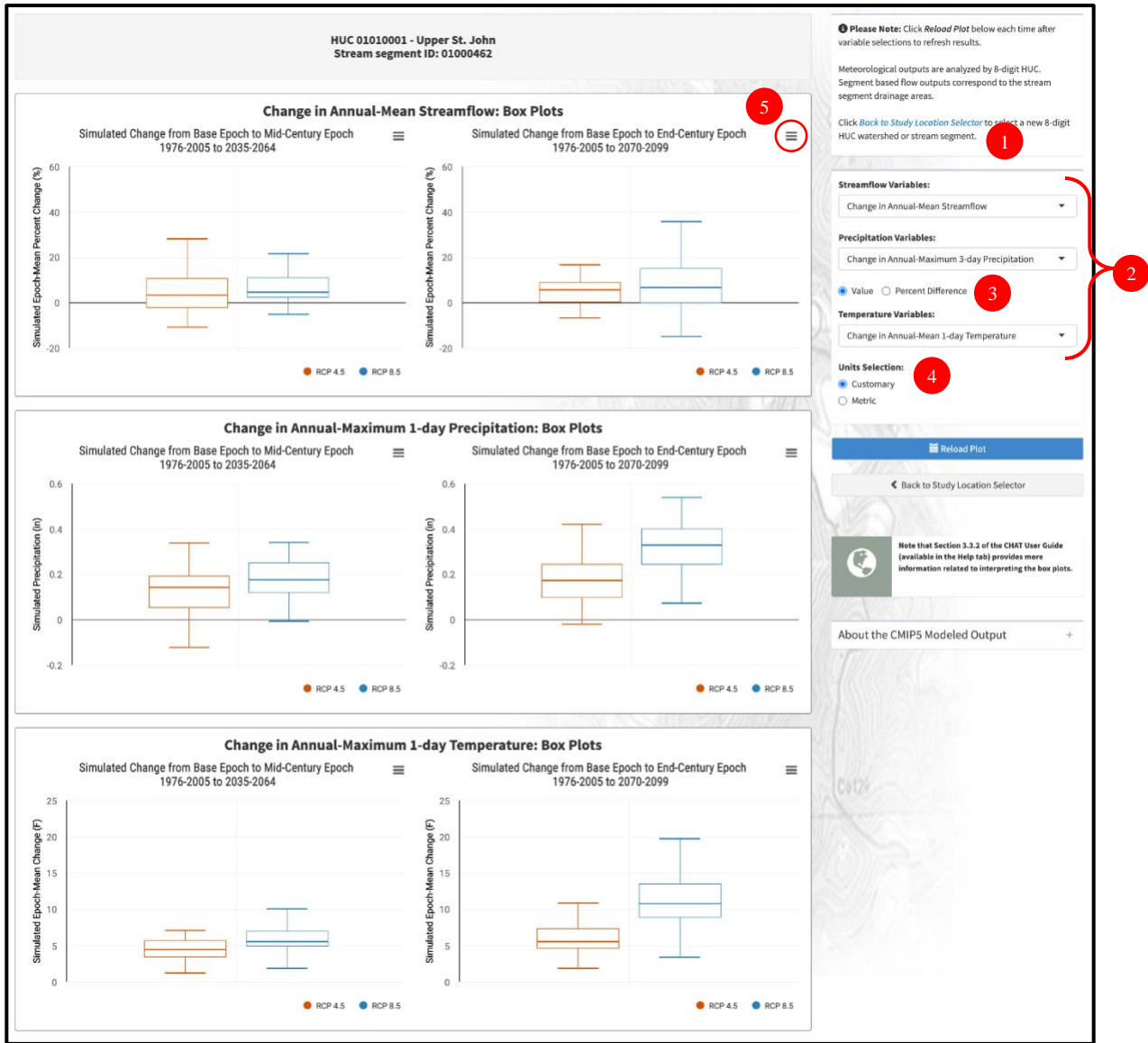A detailed explanation of how to interpret box plots is given in Section 3.5.2.

Figure 12: Annual Box Plots: Epoch-Based Changes Tab

3.6.3. Interpretation

This tab enables users to visualize simulated changes in streamflow, precipitation, and temperature at an annual resolution between two epochs of time. The sign of the simulated, epoch-based change corresponds to the directionality of the change. For example, if epoch-based changes in simulated maximum temperature is positive, this indicates that the maximum temperature in that 8-digit HUC basin is likely to increase into the future. Conversely, if epoch-based changes in simulated maximum temperature is negative, this indicates that maximum temperature is likely to decrease into the future.

The box-and-whisker markers capture the range of simulated changes generated by the suite of 32 GCMs. Half of the outputs defined based on the GCM results models span between the upper and lower horizontal lines of the box portion of the box-and-whisker plots. Excluding statistically defined outliers, the rest of the calculated outputs fall within the whiskers (aka "fences") representing the range of results derived from the 32 different GCMs. As described in Section 2.1, the spread of the calculated output reflects the uncertainty inherent to the modeling chain and assumptions applied to generate GCM-based simulations of temperature, precipitation and streamflow. As a result of this uncertainty, the median annual changes between the Base epoch and a future epoch should not be interpreted as precise predictions of future conditions.

By examining the range of simulated outputs, users can gain insight into how well-constrained (and therefore how uncertain) the changes in the simulated variable are. For example, box-and-whisker markers with a larger range (interval between whiskers/fences) relative to other epochs or scenarios exhibit greater inter-model variability in the simulated variable changes, while box-and-whisker markers with a smaller range relative to other epochs or scenarios exhibit smaller inter-model variability (and therefore more agreement amongst GCMs) in the simulated variable changes.

4. Application to Hydrologic Assessments of Climate Change Impacts

Changes in the streamflow regime, along with changes in temperature and precipitation, may have significant impacts on USACE business lines including ecosystem restoration, recreation, navigation, flood risk reduction, regulatory, emergency management, water supply, and hydropower operations. While the future simulations of streamflow, temperature, and precipitation are inherently uncertain and cannot be applied to modify numerical design calculations, CHAT output can be used to aid in the decision-making process. Outputs from the CHAT can be applied to help characterize the residual risk to a given project, basin, measure, or operating plan due to climate change. By incorporating information related to future, climate-influenced conditions into decision making and risk assessments, practitioners can support the need for the development and application of sustainable water management strategies and both structural and non-structural climate change adaptation solutions. The projected hydrologic outputs can be used, alongside other resources to bolster the argument for adding resilience into projects and management plans to address projected changes in hydrology for a given 8-digit HUC basin.

5. Change Log

Primary Changes from Version 2.1:

- **CHAT v2.2.0** released 29 April 2022
    - Changes to existing tab names:
        - Modeled Streamflow Explorer --> Modeled Time Series Explorer
        - Modeled Streamflow Trend Analysis --> Modeled Time Series Trend Analysis
    - Added a new tab "Monthly Box Plots: Epoch-Based Changes," which shows the epoch-based changes variables
    - Added multiple temperature and precipitation variables, both annual time series variables (shown in the Modeled Time Series Explorer tab and Modeled Time Series Trend Analysis tab), and epoch-based changes variables (shown in the new Monthly Box Plots: Epoch-Based Changes tab)
    - Added an option to display the new temperature and precipitation variables for the two RCP scenarios separately; note that the streamflow variables remain only available for the combined RCP-scenarios

Post-Release Updates/Patches:

- **CHAT v2.2.1** released 6 June 2022
    - Home Tab:
        - Typo in "Streamflow"
        - Added text to let users know that the tool is USACE operated
    - Explorer Tab:
        - Dynamically change significant figures on streamflow values based on magnitude (e.g., HUC 17110008).
        - Fixed titles temperature and precipitation when "Both RCP Scenarios" is selected
    - Simulated Trend Analysis Tab:
        - Visualize both RCP scenarios
        - Remove R-squared from
        - Display slope and statistical significance p-values when both RCP scenarios are displayed
- **CHAT v2.2.2** released 29 September 2022
    - Updated User Guide
    - Minor UI text changes for terminology consistency
    - Added a new tab "Reference Map"

Primary Changes from Version 2.2:

- **CHAT v2.3.0** released 28 December 2022
    - New streamflow, precipitation and temperature variables are now included in the tool.
        - **Streamflow:**
            - Annual-Mean Streamflow

- Annual-Accumulated Streamflow
- Percent Change in Epoch-Mean of Simulated Monthly Mean Streamflow
- Percent Change in Epoch-Mean of Simulated Monthly Accumulated Streamflow
- Percent Change in Epoch-Mean of Simulated Annual Mean Streamflow
- Percent Change in Epoch-Mean of Simulated Annual-Accumulated Streamflow
- Percent Change in Epoch-Mean of Simulated Annual-Maximum of Mean Monthly Streamflow

- **Precipitation:**
  - Percent Change in Epoch-Mean of Simulated Monthly Mean Accumulated Precipitation
  - Percent Change in Epoch-Mean of Simulated Monthly Max Accumulated Precipitation
  - Percent Change in Epoch-Mean of Simulated Monthly Max 3-Day Accumulated Precipitation
  - Percent Change & Change in Epoch-Mean of Simulated Annual-Maximum 3-day Precipitation
  - Percent Change & Change in Epoch-Mean of Simulated Annual-Maximum 1-day Precipitation
  - Percent Change & Change in Epoch-Mean of Simulated Drought Indicator
  - Percent Change & Change in Epoch-Mean of Simulated Annual-Accumulated Precipitation

- **Temperature:**
  - Annual-Minimum Temperature
  - Change in Epoch-Mean of Simulated Monthly Minimum Temperature
  - Change in Epoch-Mean of Simulated Annual-Mean Temperature
  - Change in Epoch-Mean of Simulated Annual-Maximum Temperature
  - Change in Epoch-Mean of Simulated Annual-Minimum Temperature

- Addition of new interface to select desired HUC-8 watershed and stream segment for downstream tabs.
- All variables have the ability to visualize projections driven by 1) individual Representative Concentration Pathways (RCPs) 4.5 or 8.5 or 2) an overlay of the projections produced using RCP 4.5 on RCP 8.5 together on the same plot.
- Users are able to view robustness metrics for mid-century and end-century model outputs for each RCP scenario on the Modeled Time Series Explorer tab.
- Users can compare baseline (historic) to mid-century (projected) and baseline (historic) to end-century (projected) values on a monthly and annual basis for streamflow, precipitation and temperature variables

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