COEQWAL Hydroclimates

Documentation Brief

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Purpose

This brief describes the five climate and hydrology conditions, referred to as Hydroclimates, used in COEQWAL modeling Scenarios. It also describes where each Hydroclimate comes from, and how it was constructed; it describes CalSim 3 model inputs only and reports no CalSim 3 results.

Overview

Every COEQWAL Scenario pairs two ingredients: a Management Strategy – a set of water management rules that people could choose to implement, and a Hydroclimate – the climate and hydrology conditions that the physical system experiences, which people cannot choose. Climate and hydrology models can help us understand what future climate and hydrology conditions might look like, but not predict them exactly. A Hydroclimate is a modeled realization of precipitation, air temperature, and river flow that serves as input to the CalSim 3 water planning model. COEQWAL uses five Hydroclimates: one historical and four representing possible future conditions. Each Management Strategy in the COEQWAL collection is modeled under all five Hydroclimates, producing the combined Scenarios that COEQWAL provides.

The four future Hydroclimates represent physically plausible, if not probable, future conditions, selected to span a range from conditions that are slightly warmer and wetter with increased river flow, to substantially warmer and drier with decreased river flow, relative to the historical record from the past century. Materially, the Hydroclimates are modified versions of a single historical time series, which is statistically adjusted to capture the characteristics (e.g., monthly and annual mean values) of climate model simulations, while preserving historical patterns in climatic and hydrologic variability.

COEQWAL assigns Hydroclimates names that relate them conceptually to different levels of climate stress. These names also correspond to numeric percentile values reflecting probabilistic levels of concern for flow changes in major California water supply basins — known as the Eight River Index (8RI) basins — using an approach previously established by the California Department of Water Resources (DWR) for the 2023 State Water Project Delivery Capability Report (SWP DCR). COEQWAL does not assign likelihoods to Hydroclimates or treat any one as more or less likely.

To understand how Management Strategies reflect management choices rather than climate differences, COEQWAL users can directly compare different Strategies within a single Hydroclimate. Similarly, to understand how Hydroclimates reflect physical climate and hydrology differences rather than management choices, COEQWAL users can directly compare different Hydroclimates within a single Strategy. The combination of different Hydroclimates and Strategies (or Scenarios) provides a comparison across potentially many different joint outcomes.

Data and Methods

"Hydroclimates" refers to modeled realizations of climate (precipitation and air temperature) and hydrology (river discharge) that constitute the climate and hydrology inputs to the COEQWAL CalSim 3 model (Figure 1). There are two sources of Hydroclimate data: physical (LOCA2 CMIP6) and statistical (DWR WGEN) modeling, described in more detail below.

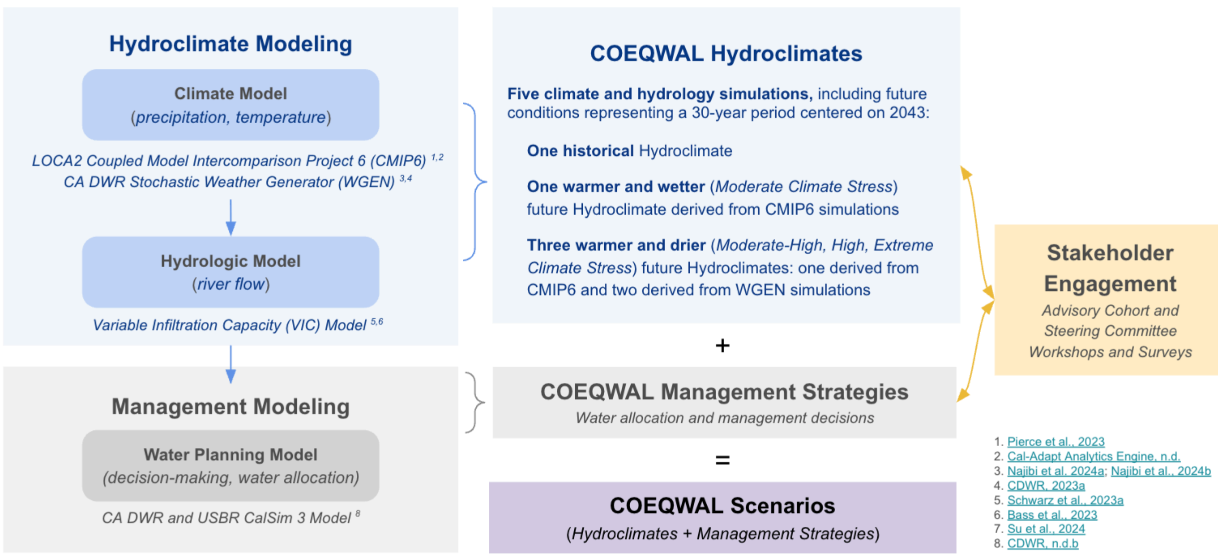

Figure 1. Summary of the COEQWAL modeling components and workflow involving hydroclimate modeling and data. Citations: 1. Pierce et al., 2023; 2. Cal-Adapt Analytics Engine, n.d.; 3. Najibi et al. 2024a; Najibi et al., 2024b; 4. CDWR, 2023a; 5. Schwarz et al., 2023a; 6. Bass et al., 2023; 7. Su et al., 2024; 8. CDWR, n.d.b

Hydroclimate Modeling

LOCA2 CMIP6

Physical Climate Model Data

Physical climate model projections are obtained from LOCA2 (Localized Constructed Analogs, version 2) (Pierce et al., 2023; LOCA2, n.d.) downscaled and bias-corrected CMIP6 (Coupled Model Intercomparison Project Phase 6) global climate model (GCM) simulations (World Climate Research Programme, n.d.). The simulations used within COEQWAL include those from one of three available Shared Socioeconomic Pathway (SSP) emissions pathways, SSP3-7.0 (SSP370), and a single ensemble member (r1i1p1f1 or r1i1p1f2), from simulations generated with 13 GCMs that were previously selected based on their demonstrated regional performance (Kalansky et al., 2024). The LOCA2 CMIP6 climate model simulations are transient, representing variations (e.g., dry and wet years) and changes (e.g., trends) over time, and span the period 1950–2100, with CMIP6 historical simulations through 2014 and projected simulations beginning in 2015. LOCA2 CMIP6 products include daily gridded data at approximately 3 km spatial resolution. Variables used in COEQWAL modeling include daily precipitation (PREC), minimum air temperature (TMIN), and maximum air temperature (TMAX). LOCA2 data are accessible through the Cal-Adapt Analytics Engine platform (Cal-Adapt Analytics Engine, n.d.) and are retrievable using the platform's documented Python packages.

Hydrologic Model Data

Climate variables, including precipitation and temperature, were used as inputs to the Variable Infiltration Capacity (VIC) macroscale hydrologic model to simulate projected land surface conditions and estimates of daily surface (runoff) and subsurface (baseflow) discharge. VIC model simulations driven *directly* by LOCA2 CMIP6 climate data are accessible through Amazon Web Services (AWS) Simple Storage Service (S3) buckets, as referenced in the Cal-Adapt Analytics Engine documentation (Cal-Adapt Analytics Engine, n.d.).

We computed estimates of monthly river flow for CalSim 3 inflow basin spatial units (rim basins), as required by the CalSim 3 model, as area-weighted discharge, aggregated from daily surface and subsurface VIC discharge and from grid cells intersecting each CalSim 3 basin, to monthly basin totals (mm per month, converted to thousand acre-feet per month). This monthly basin-average "routing" approach was validated against historical observed discharge at select representative basins and was determined to be sufficient at both daily and monthly time scales based on standard model fit and error metrics (Bass et al., 2023). This approach is also consistent with the methodology used in the 2023 Final State Water Project Delivery Capability Report (SWP DCR) (CDWR, n.d.a). We only processed VIC model discharge for CalSim 3 inflow basins; hydrologic routing and water balance computations within the Central Valley domain, including aggregation and transfer across CalSim Water Budget Areas (WBAs), are handled by CalSim 3's integrated hydrologic module.

DWR WGEN

Statistical Climate Model Data

The DWR Weather Generator (WGEN) is a statistical climate simulation model developed and refined for regions across California (Steinschneider et al., 2019; Najibi et al., 2024a; Najibi et al., 2024b; Najibi and Steinschneider, 2023; CDWR, 2023a). Select climate change simulations and associated data products were produced using WGEN for application in DWR modeling, specifically the 2023 SWP DCR (CDWR, n.d.a). The WGEN data are available at a 6 km spatial resolution; details and data are accessible and retrievable from DWR's WGEN Data and Resources website (CDWR, 2023a).

WGEN is a statistical climate model that generates stationary climate simulations, meaning the simulations represent prescribed stable change in climate conditions rather than transient temporal trends. In contrast to the CMIP6 climate simulations, select 100-year WGEN simulations (Najibi et al., 2024a; CDWR, 2023a Product A) correspond to climate conditions with different statistically-derived 'levels of concern', a probabilistic measure that captures the extremity of stress on California's water supply system (Schwarz et al., 2023a). For example, a simulation of temperature and precipitation change that is associated with a 95th percentile level of concern means that the corresponding modeled river flow is lower than that simulated by 95% of simulations generated using statistics derived from physical climate models across all 8RI basins, for April–July, within the 30 years surrounding 2043. DWR used WGEN simulations that represent 50th, 75th, and 95th percentile levels of concern, defined in this way, within 2023 SWP DCR (CDWR, n.d.a) modeling.

Hydrologic Model Data

The DWR WGEN statistical climate model simulations were used to drive the VIC model *indirectly*. This means that the WGEN climate data were used to adjust a gridded historical weather dataset that was then input to the VIC model, and used for CalSim modeling for the 2023 SWP DCR (CDWR, n.d.a). DWR provided these WGEN-driven VIC model data directly to COEQWAL upon request.

CalSim Input Formatting

CalSim 3 is a water resources planning model, jointly developed by DWR and the U.S. Bureau of Reclamation, to simulate operations of water resources infrastructure in California's Central Valley and the Sacramento-San Joaquin Delta (CDWR, n.d.b). CalSim 3 inflow basin input data consist of: the monthly basin flow described above, produced by both the physical (CMIP6) and statistical (WGEN) climate-driven VIC model; minimum and maximum daily air temperatures; and precipitation. We aggregated temperature data to monthly resolution as area-weighted averages of the 3 km and 6 km grid cells (for CMIP6 and WGEN sources, respectively) intersecting the relevant CalSim 3 spatial units. These units include ~200 subbasin areas as well as additional units required by the CalSim model (e.g., WBAs, select major reservoir inflow basins), and point locations throughout the Central Valley and Delta regions. We retained precipitation from CMIP6 and WGEN data at the daily resolution and similarly aggregated from 3 km and 6 km resolution grid cells (for CMIP6 and WGEN, respectively) using area-weighted average daily depths (mm) over each spatial unit, in accordance with CalSim 3 input formatting requirements.

Time series of monthly basin flow, monthly minimum and maximum daily temperatures, and daily precipitation – aggregated to their respective CalSim 3 spatial units – are *not* directly input into the CalSim 3 model. Instead, statistical distributions of these time series variables over a 30-year mid-century period centered on 2043 are used to adjust a set of 100-year climate and hydrologic records created specifically for the CalSim model (CDWR, n.d.a; Schwarz et al., 2023b). This adjustment employs a multi-step quantile-mapping approach, in which the statistical distribution of the 100-year record for each time series is adjusted to match that of the climate model–simulated data (from either CMIP6 or WGEN datasets). In the case of the transient CMIP6 projections, the adjustment relies on statistics from the 30-year mid-century period centered on 2043, which is consistent with the 2023 SWP DCR planning horizon.

CMIP6- vs. WGEN-derived Hydroclimates

The climate and hydrologic data derived from CMIP6 and WGEN differ in several key ways (Table 1). As a result, the climate variables and corresponding VIC-modeled hydrology produced from these two sources are not directly comparable; however, they remain comparable with respect to their statistical properties and the climate change signals they imply. As such, COEQWAL extracted statistics from both the physical (CMIP6) and statistical (WGEN) climate and hydrologic realizations and applied those statistics, via a quantile-mapping procedure, to the same historical 100-year climate and hydrologic input dataset developed for the CalSim 3 model (see CalSim Input Formatting). Thus, the 100-year CalSim 3 inputs adjusted through quantile mapping represent statistically adjusted versions of a common underlying 100-year time series, in which the magnitudes of climate and hydrologic values are modified to reflect modeled future conditions while the timing and sequence of events remain unchanged. Therefore, CalSim 3 model outputs generated using Scenarios that incorporate COEQWAL Hydroclimates derived from CMIP6 or WGEN sources *are* directly comparable.

		CMIP6-VIC	WGEN-VIC
Climate Model and Data	*Temporal structure*	Historical: 1950-2014, daily Future: 2015 - 2100, daily; transient change (Cal-Adapt Analytics Engine, n.d.)	Historical: 1921-2021, daily Future: 100-year synthetic, daily; stationary change (CDWR, 2023a)
	Spatial structure	~3km grid; LOCA2 downscaled from ~ 100km (LOCA2, n.d.; Cal-Adapt Analytics Engine, n.d.)	1/16 degree (~6km) grid (CDWR, 2023a; Najibi et al., 2024a; Najibi et al., 2024b)
Hydrologic Model and Data	*Model calibration and validation*	Performance metrics evaluated using observed discharge in gauged basins; regionalization approach used in ungauged basins (Bass et al. 2023; Su et al. 2024)	Performance metrics evaluated using historical and simulated inflows from the Sacramento Valley to the Delta (CDWR, 2022)
	Climate input process	Direct: gridded LOCA2 CMIP6 climate input to VIC (Bass et al., 2023; Cal-Adapt Analytics Engine, n.d.)	Indirect: gridded WGEN climate used to statistically adjust gridded historical climate data (CDWR, 2023a)
Climate and Hydrologic Model and Data Purpose		Generated for California's Fifth Climate Change Assessment (CA Governor's Office, n.d.)	Generated for DWR's 2023 SWP DCR (CDWR, n.d.a)

Table 1. Summary of structural differences between hydroclimate datasets generated from physical and statistical climate models.

Selected Hydroclimates

COEQWAL "Hydroclimates" are select realizations of climate (precipitation and temperature) and hydrology (river flow) drawn from the broader suite of available climate and hydrologic model simulations (see Hydroclimate Modeling). Based on iterative feedback obtained through COEQWAL project meetings, workshops, webinars, and surveys involving members of the COEQWAL project team, Advisory Cohort, and Steering Committee, the Hydroclimate Modeling team selected five Hydroclimates (see Hydroclimate Selection Process) for incorporation into COEQWAL Scenarios (Figure 1). The selected Hydroclimates (Table 2) include one historical dataset, two WGEN-based simulations, and two CMIP6-based simulations (described below).

COEQWAL Hydroclimate	Source Data	Temp. change	Precip. change	Flow change	Level of concern	Sea Level Rise
Historical	**DWR Adjusted Historical (Schwarz et al., 2023b)**	—	—	—	—	**0 cm**
Moderate Climate Stress	**LOCA2 CMIP6 EC-Earth3-Veg SSP370**	**+1.1°C**	**+4.0%**	**+3.5%**	**40th**	**15 cm**
Moderate-High Climate Stress	**DWR WGEN "50th Percentile Level of Concern"**	**+1.5°C**	**+1.5%**	**-1%**	**50th**	**15 cm**
High Climate Stress	**DWR WGEN "95th Percentile Level of Concern"**	**+1.8°C**	**-1.8%**	**-6.5%**	**95th**	**30 cm**
Extreme Climate Stress	**LOCA2 CMIP6 TaiESM1 SSP370**	**+1.9°C**	**-5.8%**	**-19.2%**	**>99.9th**	**30 cm**

Table 2. COEQWAL Hydroclimates, their source data, annual average daily temperature change (°C), change in total annual precipitation (%), change in total annual flow (%), a 'level of concern' (percentile) estimate for CalSim 3 inflow basin flow change, and the modeled sea level rise (SLR) associated with each Hydroclimate (see Sea Level Rise). LOCA2 CMIP6-based Hydroclimates represent changes estimated from a 30-year period centered on 2043 (2028-2057 relative to 1992-2021), and DWR WGEN-based Hydroclimates capture prescribed levels of change for the same 30-year planning horizon. 'Level of concern' represents a modeled statistical probability for Eight River Index (8RI) April–July runoff under the associated hydroclimate; 'level of concern' values are reported directly for DWR WGEN–derived hydroclimates and as approximate values for CMIP6-derived hydroclimates (see Risk Analysis Extrapolation).

Historical

Central Valley inflow basin temperature, precipitation, and inflow patterns reflect historical conditions. The Historical Hydroclimate uses the 100-year climate and hydrologic record developed for CalSim 3 and used in the 2023 SWP DCR (Schwarz et al., 2023b). It carries the observed variability of the historical period — wet years, dry years, and multi-year patterns — bias-corrected to remove overall time trends while preserving variability, and serves as the reference against which the four future Hydroclimates can be compared.

Moderate Climate Stress

Slightly warmer and moderately wetter conditions. This Hydroclimate reflects a slight temperature increase of +1.1 °C and a moderate 4% increase in precipitation annually over Central Valley inflow basins, which together result in a 3.5%

annual increase in modeled inflows. It is derived from a physical climate model simulation (LOCA2-downscaled CMIP6, EC-Earth3-Veg model, SSP3-7.0 emissions pathway) whose conditions correspond to an approximate, probabilistic estimate of 'level of concern' for April–July runoff across 8RI basins that ranks in the 40th percentile.

Moderate–High Climate Stress

Moderately warmer conditions with little change in precipitation. This Hydroclimate reflects a moderate temperature increase of +1.5 °C and a slight 1.5% increase in precipitation annually over Central Valley inflow basins, which together result in a 1% annual decrease in modeled inflows. It is derived from a statistical climate model (DWR WGEN) whose conditions correspond to a probabilistic estimate of 'level of concern' for April–July runoff across 8RI basins that ranks in the 50th percentile.

High Climate Stress

Much warmer and moderately drier conditions. This Hydroclimate reflects a substantial temperature increase of +1.8 °C and a moderate 1.8% decrease in precipitation annually over Central Valley inflow basins, which together result in a 6.5% annual decrease in modeled inflows. It is derived from a statistical climate model (DWR WGEN) whose conditions correspond to a probabilistic estimate of 'level of concern' for April–July runoff across 8RI basins that ranks in the 95th percentile.

Extreme Climate Stress

Much warmer and much drier conditions. This Hydroclimate reflects a substantial temperature increase of +1.9 °C and a substantial 5.8% decrease in precipitation annually over Central Valley inflow basins, which together result in a 19.2% annual decrease in modeled inflows. It is derived from a physical climate model simulation (LOCA2-downscaled CMIP6, TaiESM1 model, SSP3-7.0 emissions pathway) whose conditions correspond to an approximate probabilistic estimate of 'level of concern' for April–July runoff across 8RI basins that ranks in the >99.9th percentile.

Sea Level Rise

Sea level is expected to rise under continued climate warming. The exact level and timing for sea level rise (SLR) are uncertain but is expected to be directly correlated with the intensity of warming. Sea level is an important boundary condition for the Delta in CalSim 3, as it affects the balance of fresh and saline water and, therefore, the freshwater inflows into the Delta required to maintain certain salinity levels. CalSim 3 does not directly simulate the hydrodynamics required to quantify salinity response to flows and tides, but instead uses a computationally-efficient artificial neural network (ANN) that approximates a set of flow-salinity relationships throughout the Delta based on hydrodynamics and salinity simulations from the Delta Simulation Model II (DSM2; Jayasundara et al., 2020). Different versions of the ANN can be developed from DSM2 simulations run with modified sea level boundary conditions. When used with a CalSim 3 simulation, each modified ANN provides estimates of flow-salinity relationships under its corresponding SLR condition. DWR developed two ANNs that reflect 15 cm and 30 cm of SLR, in addition to the 0 cm SLR ANN used for historical Hydroclimate conditions.

In assigning a SLR condition to each COEQWAL CalSim 3 scenario, we sought to align SLR with the Hydroclimate inputs and followed the convention established by the 2023 SWP DCR (CDWR, n.d.a). Specifically, we use the 15 cm SLR ANN with the Moderate and Moderate-High Climate Stress Hydroclimates and the 30 cm SLR ANN with the High and Extreme Climate Stress Hydroclimates (Table 2). Additionally, Delta island consumptive use and Delta channel depletions are updated to reflect the modified meteorology of each Hydroclimate, i.e., the 2023 SWP DCR Delta depletion scenario files are associated with the WGEN-based Hydroclimates (see DWR WGEN), and the adjusted climate data with the CMIP6-based Hydroclimates (see LOCA2 CMIP6 and CalSim Input Formatting).

Hydroclimate Selection Process

To aid in the selection of COEQWAL Hydroclimates, and in association with stakeholder feedback, we evaluated CMIP6- and WGEN-derived climates and hydrology on a common statistical basis. To do this, we used a graphical comparison framework that shows Hydroclimate simulation statistics across three dimensions, modeled after DWR's stress testing framework (Schwarz et al., 2023a): change in temperature (°C), change in precipitation (%), and change in river flow (%), summarized at either annual or seasonal time scales and across the CalSim 3 inflow basins (Figure 2). For the transient CMIP6 simulations, statistics were computed over a 30-year temporal window centered on 2043, consistent with the period used for the climate change risk analysis that informed the 2023 SWP DCR (Schwarz et al., 2023b).

The COEQWAL Hydroclimate selection process ultimately relied on the WGEN-based simulations as a basis for understanding relative magnitudes of hydroclimatic change. The stationary nature of the WGEN simulations makes them particularly well suited for CalSim 3 modeling, given that CalSim 3 inputs are ultimately derived by statistically adjusting a stationary, historical 100-year climate and hydrologic record developed specifically for use within the CalSim 3 model (see CalSim Input Formatting).

The CMIP6-based Hydroclimates were selected to represent conditions that deviate from those of the WGEN-based simulations in ways identified as salient by the COEQWAL community, including a broader range of warming, precipitation, and flow conditions. Importantly, the CMIP6-based Hydroclimates do not represent linear deviations in temperature, precipitation, or flow conditions relative to the WGEN-based Hydroclimates. Rather, they are alternative simulations of possible future climate and hydrology that vary in distinct ways from the WGEN sources. Even where summary statistics of climate and hydrologic change are similar between the CMIP6- and WGEN-based sources, CMIP6 simulations can produce different spatiotemporal patterns of climate and hydrology. The extent to which such spatial variability in CMIP6-derived hydroclimate – variability that may not be present in WGEN-derived hydroclimate – propagates through the adjustment of the 100-year CalSim 3 input time series has yet to be determined and remains the subject of ongoing study.

The CMIP6-based *Extreme Climate Stress* Hydroclimate represents levels of hydroclimatic change associated with an exceedingly low probability (<<1%) based on extrapolations from the statistical distributions of temperature and precipitation change estimated in DWR's risk analysis (Schwarz et al., 2023a). A Hydroclimate future with a low probability was purposefully included in COEQWAL modeling to address community interest in the representation of climate extremes, to the extent possible within the CalSim 3 modeling framework. Accordingly, the CMIP6-based *Extreme Climate Stress* Hydroclimate provides a representation of physically plausible, if not probable, future climate and hydrology conditions.

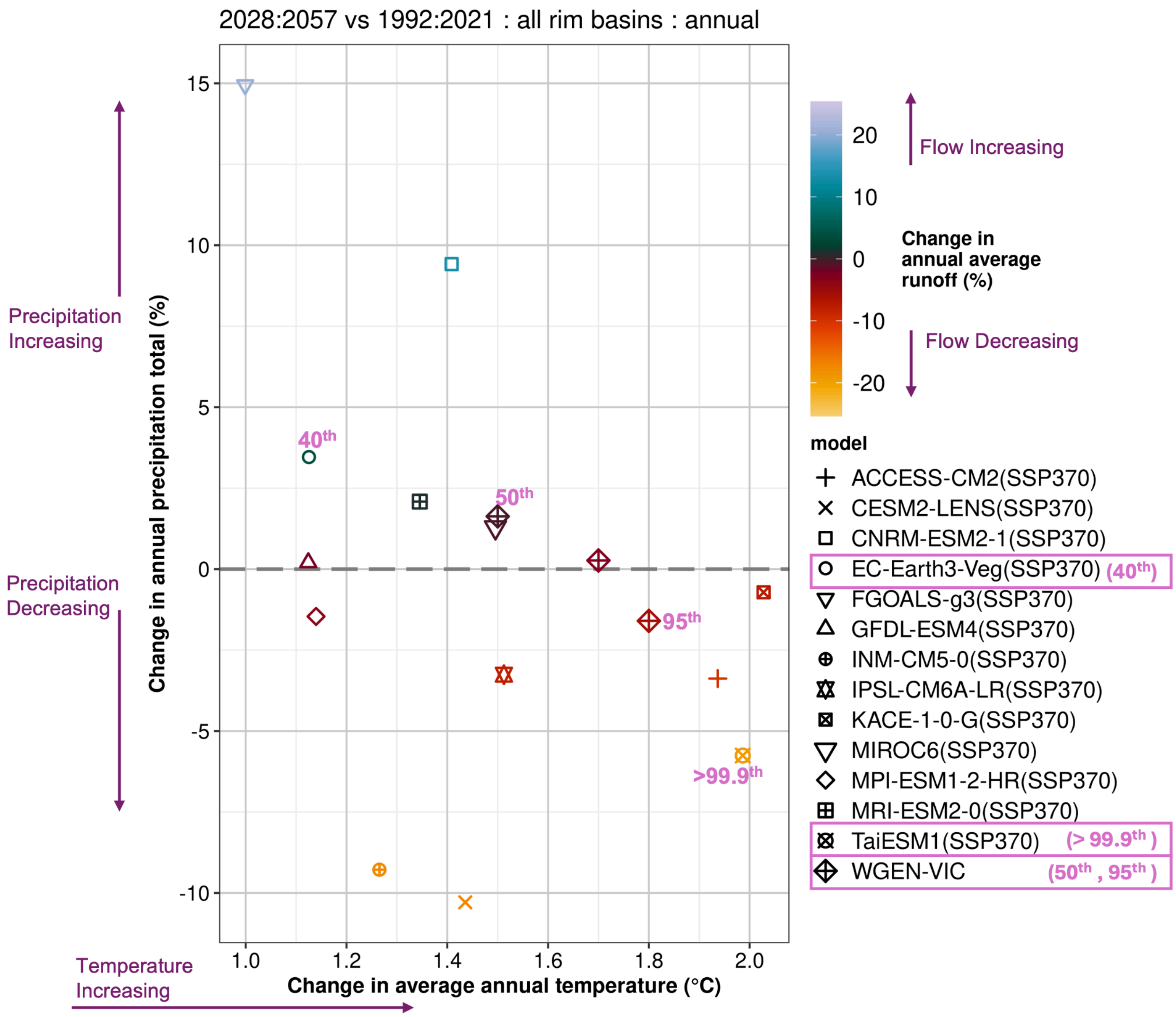

Figure 2. Change in annual total precipitation (%, vertical axis), average annual daily temperatures (°C, horizontal axis), and average total flow (%, color) summarized over CalSim 3 inflow (rim) basins. Hydroclimate data sources include LOCA2-downscaled CMIP6 GCMs and their associated VIC hydrologic model runs under SSP 370 for the modeled 30-year period of 2028-2057 relative to 1992-2021, as well as ~100 year (stationary) WGEN climate and associated VIC hydrologic model runs (point shapes). Pink text annotates the four future COEQWAL Hydroclimates and their estimated 'level of concern' with respect to Eight River Index April - July flows (see Table 2).

Risk Analysis Extrapolation

We estimated approximate 'levels of concern' for CMIP6-derived Hydroclimates by fitting a bivariate normal distribution to reference combinations of temperature and precipitation change with known percentile rankings (Table 5-5, Schwarz et al., 2023a). Distribution parameters were estimated by treating each reference combination as lying on the Mahalanobis distance ellipse corresponding to its stated percentile; the level of concern for each new scenario was then computed as the chi-squared CDF (df = 2) of its squared Mahalanobis distance from the fitted mean, with tail probabilities computed analytically. This approach follows the general framework of François et al. (2024) as applied in the DWR risk analysis by Schwarz et al. (2023a), but differs in that a bivariate normal replaces an alternative copula approach, the distribution is fitted directly to the reference percentile table rather than being derived from climate projections, and the level of concern is an exceedance probability rather than one conditioned on water system performance. Thus, the CMIP6-derived Hydroclimate levels of concern should be treated as approximate.

Hydroclimate Data Access

Data formatted for the two CMIP6-derived Hydroclimates (*Moderate Climate Stress* and *Extreme Climate Stress*), as well as additional CMIP6 model datasets that were *not* ultimately selected to represent a final COEQWAL Hydroclimate are available upon request. These data include LOCA2 CMIP6 SSP 370 temperature, precipitation, and discharge from select CMIP6 models for full historical and modeled future periods (1950-2014, 2015-2100), aggregated spatially and temporally according to CalSim 3 input requirements. Additional supplementary records of *daily* flow (only) for the same LOCA2 CMIP6 models and SSPs, as well as aggregations across custom combinations of inflow basins relevant to analysis of environmental flows are also available upon request. Other derived datasets and documentation produced during the COEQWAL project (including the most recent version of this document) are also available upon request.

All CMIP6 source data from which these COEQWAL Hydroclimate datasets were derived are publicly available and accessible as described and referenced above. The WGEN-derived climate data used for the COEQWAL *Moderate-High Climate Stress and High Climate Stress* Hydroclimates are publicly available and accessible as described and referenced above; the WGEN-derived VIC-modeled flow is not publicly available, and was acquired upon request from DWR; the CMIP6-based VIC-modeled discharge is publicly available for download (Cal-Adapt Analytics Engine, n.d.). The 100-year CalSim 3 input climate and hydrologic data, derived as adjustments of stationary 100-year historical records based on statistics from the COEQWAL Hydroclimate data, are generated as a part of the COEQWAL CalSim 3 modeling workflow, which is separately documented.