Analysis and Technical Update to the Colorado Water Plan

Technical Memorandum

Prepared for:

Colorado Water Conservation Board

Subject:

Temperature Offsets and Precipitation Change Factors Implicit in the CRWAS-II Planning Scenarios

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Section 1: Executive Summary

This memorandum specifies monthly averaged temperature offsets and precipitation change factors implicit in key planning scenarios for future year 2050: “Hot and Dry” and “Between 20th Century Observed and Hot and Dry”. A temperature offset (°C) quantifies the predicted temperature change from baseline conditions (1970 – 1999) to future conditions (2050). A precipitation change factor (unitless) is the ratio of predicted future (2050) to baseline (1970 – 1999) precipitation totals. Table 1 summarizes temperature offsets and precipitation change factors for two key scenarios, spatially averaged over the entire state.

Table 1. Summary of temperature offsets and precipitation change factors, averaged across the entire state for the “Hot and Dry” and “Between 20th Century Observed and Hot and Dry” planning scenarios.

Scenario	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
Temperature Offsets °C													
Hot & Dry	1.7	1.7	2.0	2.2	2.7	2.7	2.7	2.7	2.7	2.4	2.0	1.7	2.3
Between	1.4	1.5	1.7	1.8	2.2	2.3	2.2	2.5	2.4	2.5	1.9	1.8	2.0
Precipitation Change Factors [-]													
Hot & Dry	1.13	1.05	1.01	0.91	0.85	0.97	0.94	0.95	0.96	0.98	1.06	1.07	0.99
Between	1.14	1.23	1.10	0.93	0.90	1.00	1.00	0.95	1.06	1.05	1.10	1.10	1.05

Additionally, this memorandum reviews the logic and methodology behind the development of the planning scenarios, explains the methodology used to calculated monthly average temperature offsets and precipitation change factors, and presents and discusses the analysis results. Analysis results presented in this memorandum are provided in a directory of .csv files, shared via a Google Drive link. Additionally, temperature offset results are visualized through an interactive ArcGIS Story Map.

Section 2: Background

The primary performance metric of a water supply system is the ability to meet beneficial water use demands, such as agricultural water use, ecological flows, or reservoir storage withdrawals. One metric of water supply stress is the basin-scale balance between runoff and beneficial consumptive use. High stress conditions manifest when runoff is low and consumptive use is high, whereas low stress conditions emerge when runoff is high and consumptive use is low. Under this conceptual umbrella, CRWAS-II identified seven future planning scenarios intended to explore the full range of water supply stress conditions plausible for the state of Colorado in 2050. Two of these scenarios have been used by the state as key planning scenarios, known as “Hot and Dry” and “Between 20th Century Observed and Hot and Dry”.

The foundation of the CRWAS-II scenario development process is a set of model runs conducted by the U.S. Bureau of Reclamation (USBR) simulating future hydrologic conditions for the United States (Bureau of Reclamation, 2013). Specifically, the Variable Infiltration Capacity (VIC) model (Liang, Lettenmaier, Wood, & Burges, 1994) was forced with predicted climate conditions from the Coupled Model Intercomparison Project (CMIP) Phases 3 and 5, commonly known as CMIP3 (Meehl et al., 2007) and CMIP5 (Taylor et al., 2012). In total, USBR produced 209 VIC simulations generated from 112 CMIP3 and 97 CMIP5 model predictions, providing an ensemble of future hydrologic projections.

Next, each of the USBR hydrologic model projections were summarized for the state of Colorado by calculating average runoff and consumptive irrigation requirement (CIR) anomalies between current and future 2050 conditions across each 1/8-degree grid cell of the model domain covering the state. Consumptive irrigation requirement (CIR) is the depth of water required to satisfy the gap between potential and actual evapotranspiration. When plotted on a range-normalized axis, the relationship between runoff and CIR anomalies is approximately linear and represents a gradient of water supply stress conditions (Figure 1, blue points). When runoff is high, CIR is low, and the system is minimally stressed (upper right quadrant of Figure 1). Conversely, when runoff is low, CIR is high, the system is maximally stressed (lower left quadrant of Figure 1).

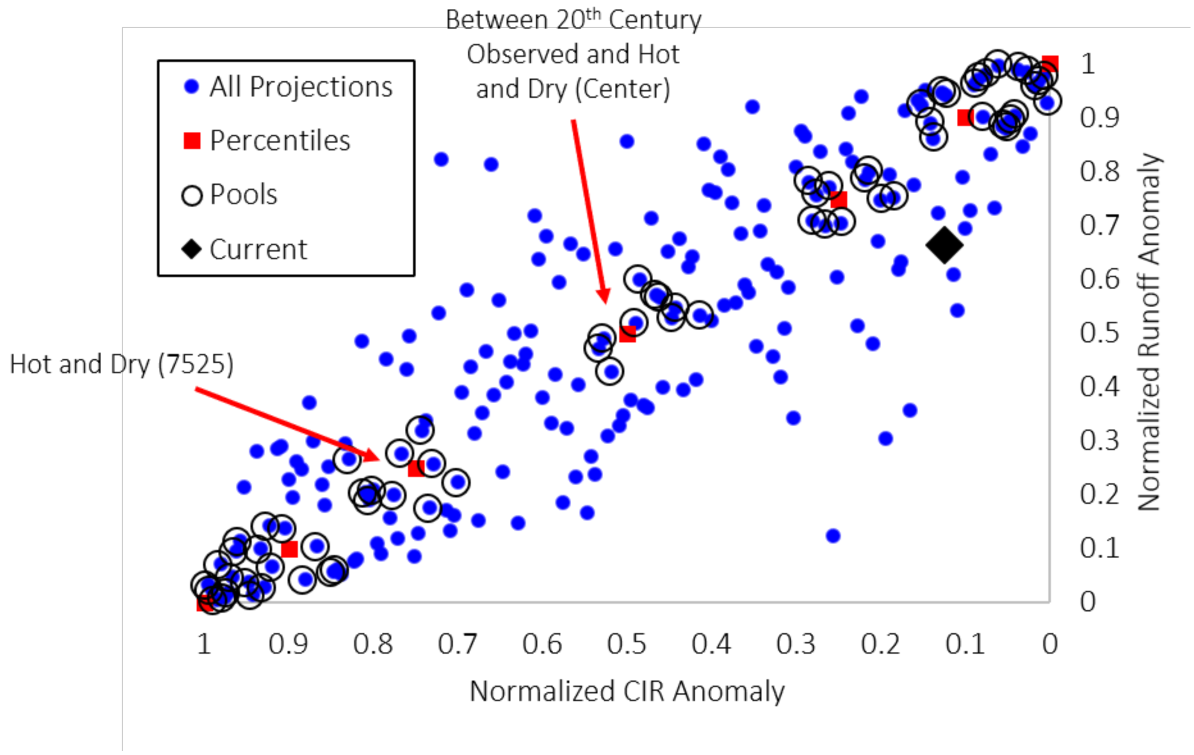

Figure 1. A linear relationship emerges between state-averaged normalized consumptive irrigation requirement (CIR) and normalized runoff anomalies in the 209 VIC projections conducted by the U.S. Bureau of Reclamation (blue points). The point cloud of VIC projections is discretized by seven characteristic points located at select CIR and runoff percentile combinations (red points). A nearest neighbor sampling method is then used create pools associated with characteristic points by identifying the 10 VIC projections nearest each point (black circles identifying blue points).

Because the relationship between runoff and CIR anomaly synthesizes water supply stress, CRWAS-II planning scenarios were defined in the runoff/CIR anomaly space (i.e. Figure 1). The runoff/CIR anomaly space was discretized by seven characteristic points, located at select runoff and CIR percentile combinations (Table 1, Figure 1 red points). A nearest neighbor clustering approach was used to identify the 10 projections nearest each characteristic point, creating seven pools of 10 projections corresponding to each characteristic point (Figure 1 black circles).

Table 2. The cloud of VIC projections in consumptive irrigation requirement (CIR) – runoff space (i.e. Figure 1) was discretized by seven characteristic points located at select runoff and CIR percentiles. This table specifies the location of those points. Additionally, each characteristic point and associated pools of VIC projections are referred to by a common designation, such as "upper right", or "lower left".

Designation	CIR Percentile	Runoff Percentile
Lower Left (ll)	100%	0%
9010	90%	10%
7525 ("Hot and Dry")	75%	25%
Center (c) ("Between 20th Century Observed and Hot and Dry")	50%	50%
2575	25%	75%
1090	10%	90%
Upper Right (ur)	0%	100%

For each projection in a pool, monthly changes in temperature and precipitation were calculated between the simulated baseline condition (1970 – 1999) and the simulated future condition (2035-2054). Monthly changes in temperature are expressed as offsets (future = baseline + offset, units °C) and monthly changes in precipitation are expressed as factors (future = baseline * factor, unitless). Monthly temperature offsets and precipitation change factors were averaged across all 10 projections in each pool, yielding a set of characteristic temperature offsets and precipitation change factors for seven scenarios.

Finally, pool-averaged monthly offsets and change factors were applied to historical daily temperature and precipitation data using a "delta" approach to create a set of seven climate-impacted forcing scenarios, colloquially referred by their designation terminology in Table 1. These scenarios were used to run a separate VIC model for the state of Colorado, and ultimately predict changes in water resources under future climate change conditions. In this technical memorandum, we report pool-averaged monthly temperature offsets and precipitation change factors at three spatial resolutions, 1) state, 2) basin, and 3) HUC10, in order to improve stakeholder understanding of how each scenario is related to specific changes in climate (in terms of temperature and precipitation). Specific emphasis is placed on two key scenarios: "Hot and Dry" and "Between 20th Century Observed and Hot and Dry".

Section 3: Methodology

Temperature offsets and precipitation change factors for each of the seven planning scenarios, were quantified over three spatial extents of interest; 1) state, 2) basin, and 3) HUC10 (Table 2). Temperature offsets and precipitation change factors are available at every 1/8-degree grid cell of the hydrological model used in CRWAS-II. Using GIS software, we identified model grid cells located within or partially within 1) the Colorado state boundary, 2) the boundaries of 8 major drainage basins within the model domain, and 3) the boundaries all HUC10s within the model domain. Once we identified model grid cells corresponding to each spatial extent of interest, we calculated a weighed spatial average of temperature offsets and precipitation change factors for each month of the year. Spatial averages were weighted by the fraction of a spatial extent of interest accounted for by each model grid cell. Grid cells that partially reside within a spatial extent of interest were given less weight than those residing completely within the boundaries.

Table 3. Descriptions of the spatial extents of interest considered in the analysis.

Spatial Extent of Interest	Description
State	State boundaries of Colorado as defined by a TIGER/Line Shapefile obtained from the U.S. Census Bureau
Basin	8 major drainage basins: South Platte, North Platte, Arkansas, Colorado, Gunnison, San Juan/Dolores, Yampa/White, Rio Grande
HUC 10	575 Hydrologic Unit Code (HUC) 10 watersheds located both completely or partially within the state boundaries of Colorado.

Section 4: Results and Discussion

Monthly average temperature offsets and precipitation change factors over each spatial extent of interest for seven 2050 planning scenarios are provided in an attached file directory, shared via Google Drive (Appendix). At the state-wide level, annual average temperature offsets (arithmetic mean across 12 months) range from 1.6 – 3.0 °C and precipitation change factors range from 0.88 to 1.20 across all scenarios (Table 3). The weighted average precipitation change factors, weighted against mean monthly state-wide precipitation totals, range from 0.86 - 1.19. The hottest scenario is "Lower Left" and the coolest scenario is "1090". The wettest scenario is "Upper Right" and the driest scenario is "Lower Left" (by weighted mean precipitation change factor, Table 3, row 4).

Table 4. State-wide, annual average temperature offsets and precipitation change factors for each of the seven planning scenarios, year 2050. [a]Annual mean precipitation change factors are calculated as an arithmetic mean of monthly change factors. [b]Weighted mean precipitation change factors are calculated as a weighted mean of monthly change factors, where the average monthly precipitation totals across 266 NOAA precipitation gauges throughout the state (Figure 4) are used as weights.

Scenario designation	Annual Mean Temperature Offset (˚C)	Annual Mean Precipitation Change Factor [-][a]	Weighted Mean Precipitation Change Factor [-][b]
Lower Left (ll)	3.0	0.88	0.86
9010	2.8	0.94	0.92
7525 ("Hot and Dry")	**2.3**	**0.99**	**0.97**
Center (c) ("Between 20th Century Observed and Hot and Dry")	**2.0**	**1.05**	**1.02**
2575	2.1	1.08	1.08
1090	1.6	1.11	1.10
Upper Right (ur)	2.2	1.20	1.19

There is a seasonal signal in the magnitude of state-wide average temperature offsets, with most scenarios showing greater offset magnitudes in the late summer and early fall (August and September) (Figure 2). However, temperature offsets for scenarios "1090", "2575" and "upper right" exhibit contradictory annual patterns. State-wide average precipitation change factors exhibit a common seasonal variation across scenarios, with the greatest change factors in the early winter (December and January) (Figure 3). Some months will encounter an increase in precipitation (change factor >1) and others will experience a decrease in precipitation. Most of the scenarios show less spring and summer precipitation, and more winter precipitation (Figure 3).

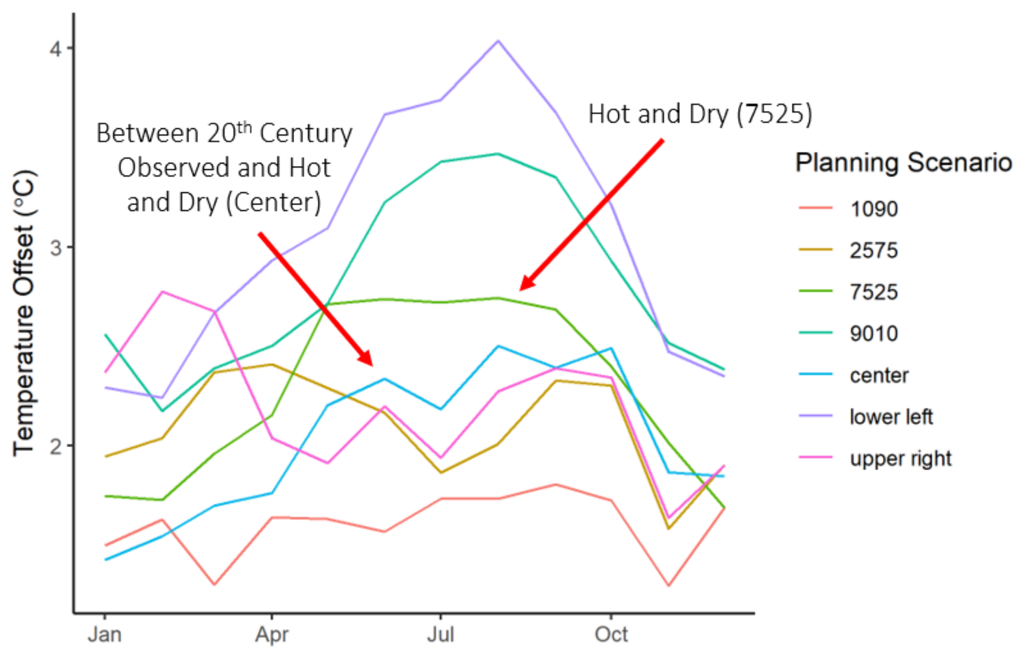

Figure 2. State-wide monthly temperature offsets for seven planning scenarios.

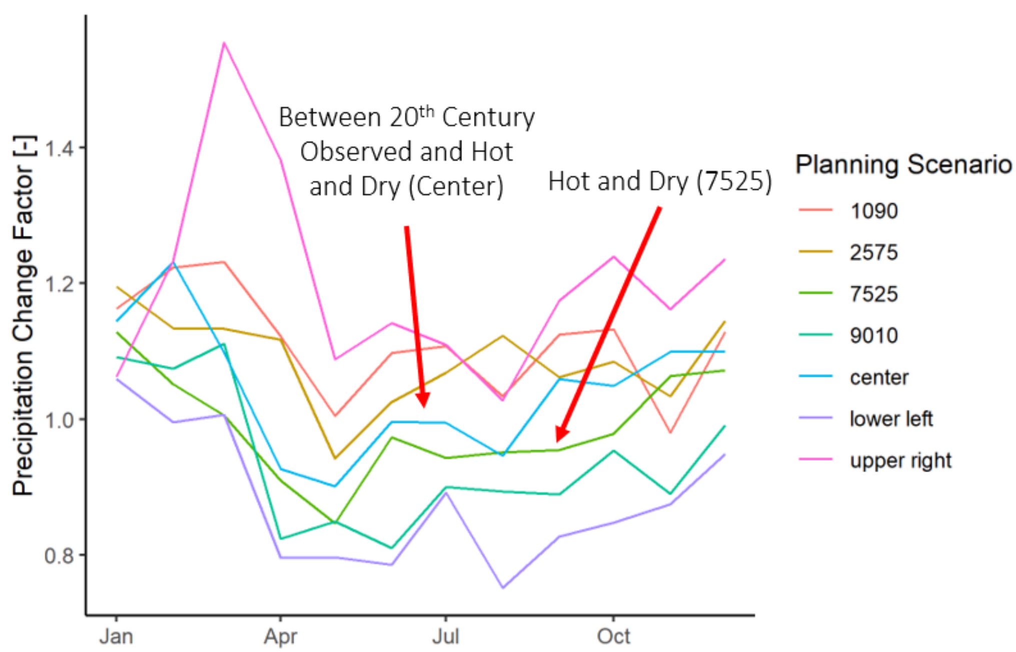

Figure 3. State-wide monthly precipitation change factors for seven planning scenarios.

When interpreting precipitation change factors, it is important to recall that future precipitation is predicted by multiplying monthly change factors by historical monthly precipitation totals. In this sense, precipitation change factors are informative for predicting the direction of change (more or less), but less intuitively describe the magnitude of future change. To understand the magnitude of future precipitation change, one must account for historical monthly precipitation trends (Figure 4). While all scenarios show the greatest change factors during the winter, winter precipitation in Colorado is relatively low, compared to spring, fall and summer (Figure 4). A weighted mean of monthly precipitation change factors, using historical monthly precipitation totals as weights, provides a more holistic summary (Table 3, row 4). Because of the non-uniform distribution of annual precipitation (i.e. some months are wetter/drier than others), caution should be applied when interpreting the arithmetic mean of precipitation change (Table 3, row 3).

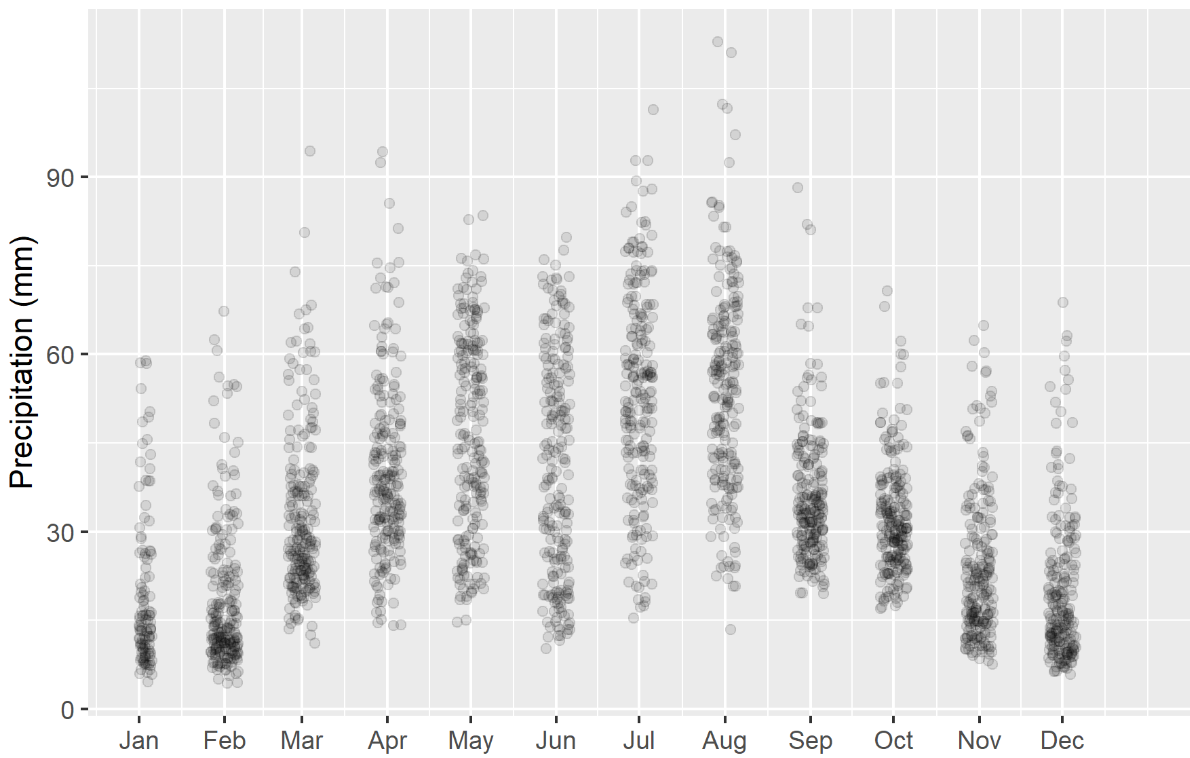

Figure 4. Monthly precipitation normal from 266 NOAA climate stations throughout the state of Colorado. It is critical to account for monthly variation in precipitation totals when interpreting precipitation change factors. Data shown in this plot were obtained from NOAA Climate Data Online (https://www.ncdc.noaa.gov/cdo-web/)

The range of state-wide annual averaged temperature offsets and precipitation change factors implicit in the seven planning scenarios spans the greater distribution of temperature offsets and precipitation change factors associated with the larger ensemble of CMIP 3 and 5 simulations used to force USBR VIC simulations (Figure 5). There is a clear relationship between precipitation change factors and temperature offsets implicit in the seven planning scenarios, where an increase in temperature offset corresponds to a decrease in precipitation change factor. This is a somewhat happenstance result because the seven planning scenarios were identified based on VIC-simulated runoff and CIR, not temperature and precipitation. However, it is intuitive that scenarios with warmer air temperatures and less precipitation would yield less streamflow and higher CIR in VIC model simulations. While the seven planning scenarios do not probe the extremes of the CMIP 3 and 5 future climate distribution, particularly the upper right (hot and wet) and lower left (cool and dry) quadrants of Figure 5, they do intentionally cover the full distribution of VIC-simulated future water supply stress (Figure 1).

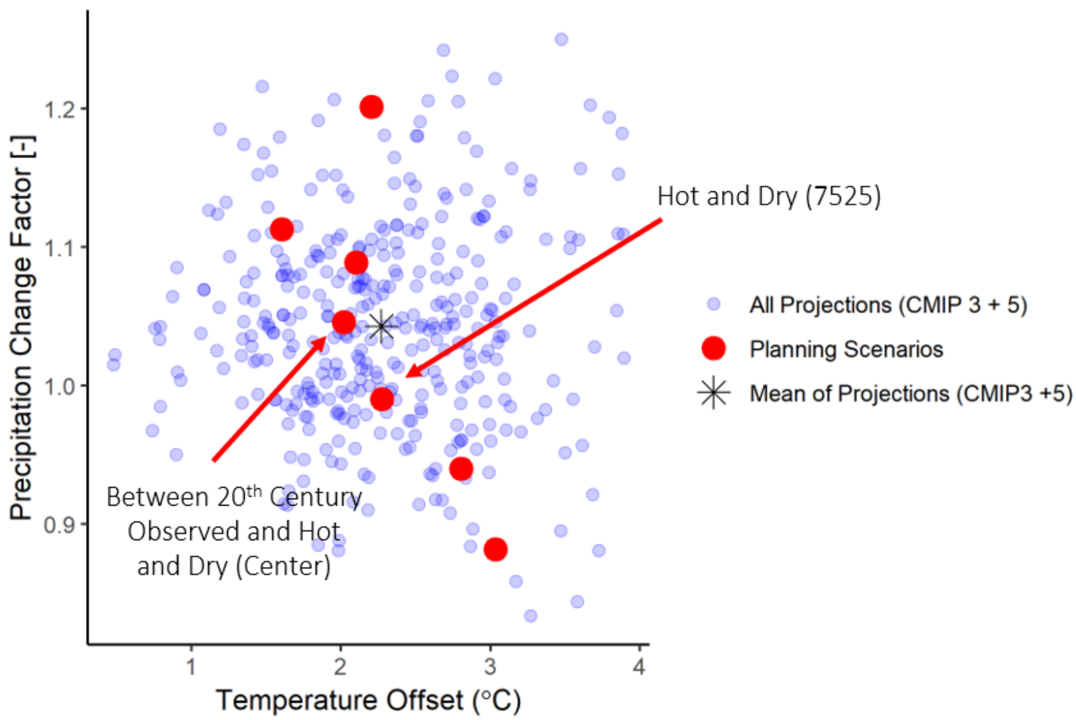

Figure 5. State-wide annual mean precipitation change factors plotted as a function of temperature offsets for all CMIP 3 and 5 model runs used to force the USBR VIC projections (blue points) and the seven planning scenarios identified by CRWAS-II.

Subtle spatial variations in temperature offset are apparent in all seven planning scenarios (Figure 6). Most notably for scenario upper right, annual average temperature offsets are greater for the western part of the state, relative to the eastern part of the state. A more complete visualization of annual-average and monthly temperature offsets at the state, basin, and HUC10 level will be made available through an ArcGIS Online Story Map at: https://arcg.is/1nyzSO.

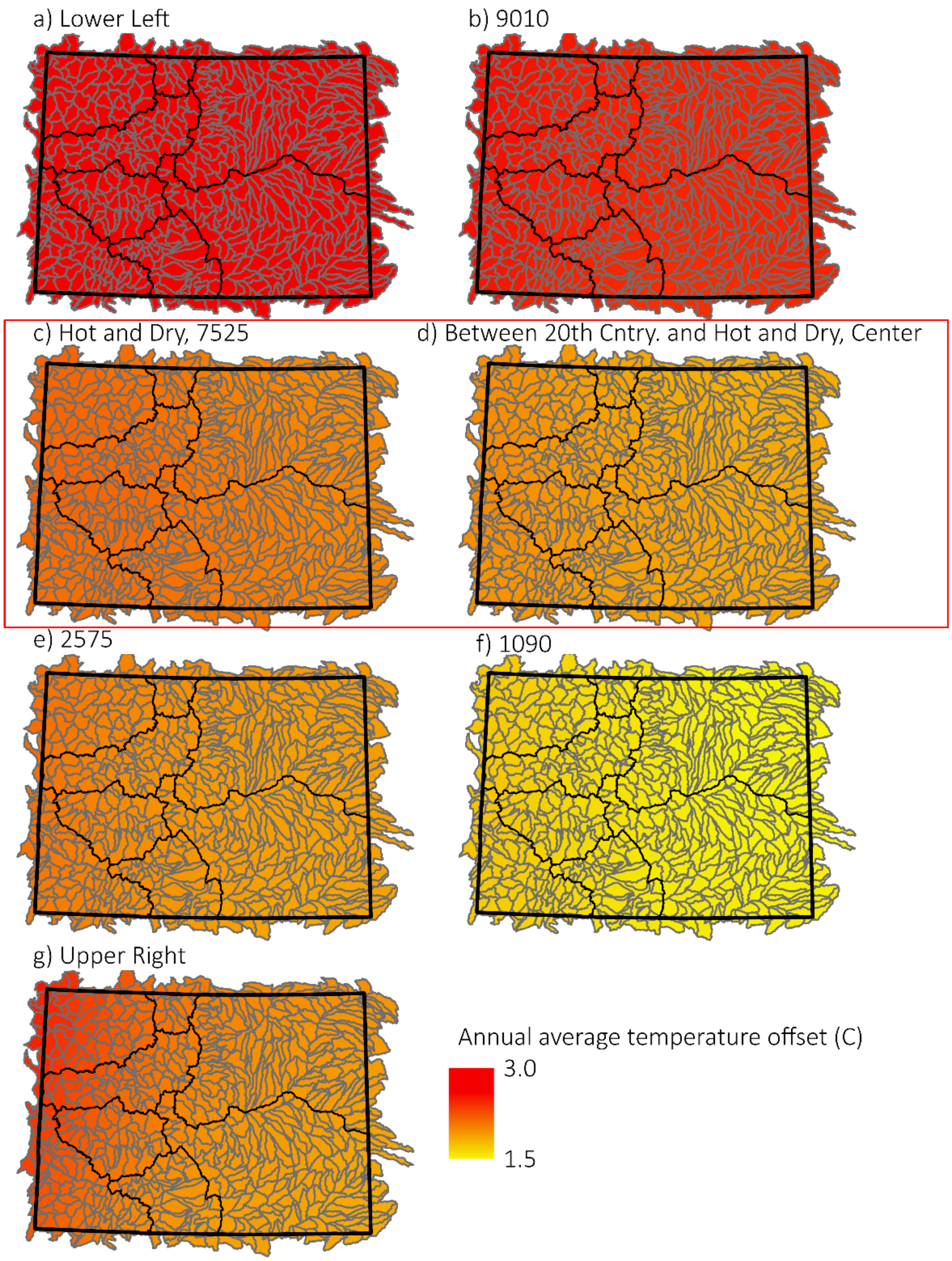

Figure 6. Annual averaged variations in temperature offset at the HUC10 level throughout the state. Each panel (a-g) represents a different planning scenario and the color scale indicates the magnitude of the temperature offset. 8 Major river basins and the state boundaries are traced with solid black lines. The “Hot and Dry” (c) and “Between 20th Century Observed and Hot and Dry” (d) scenarios are highlighted in a red box.

Section 5: Summary

- Seven CRWAS-II planning scenarios were developed to cover a distribution of potential future water supply stress conditions predicted by USBR VIC projections forced by an ensemble of CMIP3 and CMIP5 climate model outputs (Figure 1). Two of these scenarios were embraced by the state as key scenarios: "Hot and Dry" (7525) and "Between 20th Century Observed and Hot and Dry" (Center).
- State-wide, annual-average, temperature offsets implicit in the seven CRWAS-II scenarios range from 1.6 – 3.0 °C (Table 3). **The "Hot and Dry" (7525) scenario corresponds to a 2.3 °C offset, and the "Between 20th Century Observed and Hot and Dry" (Center) scenario corresponds to a 2.1 °C offset.**
- State-wide, annual-average (arithmetic mean), precipitation change factors implicit in the seven CRWAS-II scenarios range from 0.88 to 1.20 (Table 3, row 3). Weighted mean annual precipitation change factors range from 0.86 to 1.19 (Table 3, row 4). **The "Hot and Dry" (7525) scenario corresponds to a precipitation change factor of 0.99 (1% decrease in annual precipitation), and the "Between 20th Century Observed and Hot and Dry" (Center) scenario corresponds to a precipitation change factor of 1.05 (5% increase in annual precipitation).**

Table 5. Summary of temperature and precipitation changes expected for the "Hot and Dry" (7525) and "Between 20th Century and Hot and Dry" (Center) scenarios.

Scenario	Temperature Change	Precipitation Change
Hot and Dry	2.3°C	-1-3%
Between 20th Century Observed and Hot and Dry	2.1°C	+ 2-5%

- Temperature offsets and precipitation change factors for each of the seven CRWAS-II planning scenarios are provided in an attached file directory in .csv format. Results are provided for three spatial extents of interest: state, basin, and HUC10.
- Temperature offsets for each of the seven CRWAS-II planning scenarios are explorable through an ArcGIS Online Story Map, covering three spatial extents of interest: state, basin, and HUC10.

References

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Appendix A: Data Access and Visualization

Analysis result data can be accessed through the following Google Drive link:
https://drive.google.com/drive/folders/1LKcm9SLVRqEvunoY-LpQZJMycrd-Uhhw?usp=sharing

Anyone with the link above can both view and edit the information within the file directory. A brief README file explains where information is stored within the directory and provides meta data necessary to understand and use the data.

Visual exploration of temperature offset results is available through at ArcGIS Online Story Map at:
https://arcg.is/1nyzSO