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Independent Peer Review of the State Water Project–Delivery Capability Report Part 2: Risk Informed Future Scenario Development

An individual letter review for the Delta Science Program

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General comments

This report introduces and documents a new approach and the detailed procedures developed by California Department of Water Resources (DWR) to generate risk-informed future climate scenarios for the State Water Project (SWP) Delivery Capability Report (DCR), which is issued by the SWP every two years. The new approach was demonstrated using a set of daily temperature and precipitation data downscaled and bias corrected from the multi-model ensemble of the Coupled Model Intercomparison Project Phase 6 (CMIP6) using the Localized Constructed Analogs (LOCA2) method to construct a bivariate probability density function of temperature and precipitation changes between (1992-2021) and (2028-2057). Combining the future climate scenarios with system performance derived from system stress test, future temperature and precipitation changes corresponding to different levels of concern were identified. These future changes in temperature and precipitation were applied to the historical daily meteorological time series to generate traces of temperature and precipitation that allow users to examine how historical drought events may unfold in the future. The report further documents how these scenarios of daily meteorology alone and in combination with sea level rise scenarios for different levels of concern can be used to support hydrologic and water resource modeling to evaluate the system response to future changes affecting water delivery. The report also discusses the differences between the top-down and bottom-up methods previously used by DWR to generate future climate scenarios with the new approach that hybridizes the top-down and bottom-up methods.

While the report generally provides sufficient information on the new approach and the detailed procedures, the documentation can be improved for completeness, accuracy, and clarity so that the method and procedures are well understood, the results are reproducible by independent researchers, and the users of the future climate scenarios can correctly interpret the results, incorporate the information into their frameworks and tools, and make adjustments to the scenarios as needed to address their planning requirements. Generally, the figures in the report should be better explained using more detailed figure captions. Section 5.5 on the use of weather generator to develop climate scenarios for the system stress test and for supporting hydrologic and water operation modeling requires major revision to better explain the methodology, such as whether the stochastic weather regimes were used in the procedures and why and how precipitation scaling was applied.

Compared to the previous top-down and bottom-up approaches, the hybridized approach to develop future climate scenarios provides enhanced information for water users about potential future conditions and system reliability risks. This is because uncertainty in future temperature and precipitation changes is encapsulated by a fitted probability density function and the future climate scenarios can be combined with the system response surface to determine the specific temperature and precipitation changes for different levels of concern. The future climate scenarios meet the three characteristics requested from the State Water Contractors (page 5-3).

Future updates of the new approach may consider several areas for improvements by: (1) maximizing the use of the CMIP multi-model ensemble and the multi-model large ensemble simulations not limited to those downscaled by LOCA2; (2) developing climate scenarios separately for different Shared Socio-economic Pathway (SSP) scenarios; (3) providing monthly instead of annual temperature and precipitation changes to account for changes in precipitation seasonality; (4) reducing the time steps of the CalSim 3 model to address potential impacts of changing extreme precipitation and runoff events on system operation; (5) examining the effect of increasing CO2 concentration on plant water use efficiency that affects evapotranspiration, hence runoff; and (6) developing a more holistic approach for scenario development that accounts for precipitation changes induced by both thermodynamic and dynamical effects that affect consequences as well as likelihood for climate risk assessment.

Specific comments

Charge question 1

Is the procedure developed by DWR appropriately documented? Is there anything missing from the documentation?

This report discusses the needs and requirements for risk-informed future climate scenarios and the methods developed by DWR to produce such scenarios for the State Water Project (SWP) Delivery Capability Report (DCR). The report briefly introduces the top-down and bottom-up approaches used in the past to develop future climate scenarios for water resource planning throughout California state. In recognition of the pros and cons of separate top-down and bottom-up approaches, DWR developed a new hybridized approach to maximize their strengths and minimize their drawbacks. The hybridized approach is documented in several chapters, each focusing on specific steps of the new approach as summarized schematically in Figure 5-2.

While the new approach represents significant improvements over the top-down and bottom-up approaches used in the past, the documentation of the new approach can be improved for completeness, accuracy, and clarity so that the methods are well understood, the results are reproducible by independent researchers, and the users of the future climate scenarios can correctly interpret the results, incorporate the information into their frameworks and tools, and make adjustments to the scenarios as needed to address their planning requirements. Specific suggestions for improving the documentation of the procedure to develop future climate scenarios are explained below.

1. As a general observation, many figures included in the report can be better explained using more informative figure captions. Often the readers are left to guess what the figures are trying to convey or what some specific aspects of the figures mean. While the contents may be obvious to the authors of the report, they may not be for the broad range of readers with different levels of familiarity with the scientific or technical aspects of the study. I recommend the authors to adopt the standard of peer-reviewed journal publications in explaining the figures using more informative figure captions such that the figures and their captions are self-explanatory without extensively reference to the text.

2. Figure 5-1 can be improved to explain the top-down and bottom-up approaches more accurately. For the top-down approach, each icon represents information or data being passed to the icon below as symbolically illustrated by the blue arrow. For the bottom-up approach, no information/data is passed from “system response surface” to “climate model ensemble” as suggested by the blue arrow. Instead, the “system response surface” and “climate model ensemble” are to be combined to produce “system performance prediction”. A more accurate schematic of the

bottom-up approach or a more detailed figure caption explaining the graphics would be useful to help the readers understand the approach.

3. Figure 5-2 is another example of a figure that can use a longer figure caption to explain the ideas. For example, the figure caption can briefly explain what the color shading in the top left panel means. Also, for illustrative purposes, the two spatial maps of California should be visually different to illustrate the baseline and the altered future conditions.

4. Page 5-6 line 11: “over the next century” should be “over this century”.

5. Page 5-6 line 25: This is the first mention of the LOCA2 datasets. For completeness, a very brief explanation of the LOCA2 downscaling approach would be useful for readers who may not be familiar with it. It might also be useful to mention that LOCA2 is also used in the Fifth National Climate Assessment report.

6. Page 5-7 lines 3-4: For completeness, it would also be helpful to provide a one or two-sentence summary of how Krantz et al. (2021) select the models.

7. Page 5-7 lines 15-16: Consider providing a justification for why other Hot GCMs are preserved. As discussed in Hausfather et al. 2022, hot models can be included because there is still a small likelihood that TCR can lie outside of 1.4-2.2 degrees.

8. Page 5-12 line 1: “average monthly precipitation and minimum and maximum air temperature” should be “average monthly precipitation and daily minimum and maximum air temperature”.

9. Page 5-14 line 29: “The followings steps” -> “The following steps”.

10. Page 5-15 line 4: It would be useful to explain why the future climate period covers the specific period of 2028-2057, because the mid-point is 2043, which is 20 years from 2023, but this may not be obvious to the readers and is not explained until Page 5-26 lines 5-6.

11. Page 5-17 line 5: I would change “independent of natural variability” to “with reduced influence of natural variability” as averaging over a small number of initial-conditions ensemble members cannot completely get rid of the effect of natural variability.

12. Page 5-20 lines 3-4: “lower panel” and “upper panel” should be switched.

13. Page 5-20 line 19-20: Suggest changing “long-term climatic stochasticity” to “decadal climate variability”.

14. Page 5-21 line 19: Remove “additional”.

15. Page 5-22 lines 18-20: The whiskers of the box plots in Figure 5-8 correspond to model uncertainty. Hence the longer whiskers for SSP585 compared to SSP245 or SSP370 and the longer whiskers for 2070 compared to 2043 do not imply “increasing variance in precipitation” as noted in line 20. Rather the longer whiskers mean larger model uncertainty in projecting future precipitation change, which is due to model differences in hydrologic sensitivity (% change in precipitation per ^{o}C). The larger warming in SSP585 compared to SSP245 and during 2070 compared to 2043 amplifies model differences in % change in precipitation, which is the product of the hydrologic sensitivity and the warming.

16. Page 5-23 lines 3-4: As explained above, “increasing precipitation variability enhanced with additional warming” should be “larger model uncertainty in projecting precipitation changes with larger warming”.

17. Page 5-23: The caption of Figure 5-8 should explain what the crosses and bars mean.

18. Page 5-24 Figure 5-9: This figure needs more explanation. How should the readers compare your estimated values shown in Figure 5-8 with the values shown in the table of Figure 5-9? Should they be comparing your estimated values shown by the bars (median values?) in Figure 5-8 with the median values shown in the table?

19. Page 5-27 line 13: “historical experienced” -> “historically experienced”.

20. Page 5-27 line 28: “distributed the Sacramento soil moisture …” -> “distributed Sacramento soil moisture …”.

21. Page 5-27 lines 29-30: Please add references for the SAC-SMA and CalLite models. Have any previous works demonstrated that SAC-SMA and CalLite reasonably capture the behaviors of the VIC and CalSim 3 models?

22. Page 5-27 lines 33-36: The 7% scaling could be better explained to justify its use in developing future precipitation scenarios. More specifically, based on Najibi and Steinschneider (2023), the 7% scaling is only applied to the 99th percentile non-zero precipitation, which is well justified, but lines 33-36 seem to suggest that the scaling is applied to the annual precipitation or mean precipitation and additionally, extreme precipitation is also scaled.

23. Page 5-30 Figure 5-13: This figure seems to indicate that all the performance metrics are more sensitive to precipitation than temperature as all the circles lie beneath the 1:1 line. If so, this point might be worth mentioning.

24. Page 5-33 Figure 5-14: Shouldn’t the tiny dots have the same colors as the background color shading where they overlap? If the colors of the tiny dots are intentionally darkened so that they are more visible from the background color shading, this should be explained in the figure caption.

25. Page 5-36 line 11: (see Figure 5-16) should be (see Figure 5-17). To help explain how the most likely combination of the two stressors for a given level of performance is identified, one could add contours of constant percentile values of the temperature and precipitation changes in Figure 5-17. The red circle should be where the performance front that separates the red dots from the grey dots intersects with the contour closest to the center (green circle).

26. Section 5.5. This section describes the use of weather regime-based stochastic weather generator (WGEN) to scale the stationary historical daily meteorological data with temperature change and percentage precipitation change identified for

each level of concern. This section first describes WGEN as a stochastic generation approach that is used to produce a database of weather regimes that serve as proxies for specific regional weather patterns (or atmospheric circulation patterns), and these weather patterns are then used to generate daily weather (e.g., daily temperature and precipitation). However, this key aspect (stochastic weather generator) of WGEN is not actually used in the hybridized approach. Instead, only the WGEN module for temperature and precipitation scaling is applied to scale the historical daily precipitation and daily maximum and minimum temperature by combinations of step changes in temperature and percentage change in precipitation for the stress test (step 1 of Figure 5-2 and Section 5.3.1-5.3.2). Similarly, the scaling module of WGEN is used to scale the historical daily precipitation and daily maximum and minimum temperature by the temperature and precipitation changes determined for each level of concern. The stress test process seems to be described in the paragraph starting from line 23 of page 5-41 and repeated again in the next paragraph starting from line 6 of page 5-42. If my understanding is correct, the stress test is constructed by adding perturbations to the 104-year of record, not applied to some synthetic weather generated by WGEN based on weather regime. However, the paragraph starting on line 16 of page 5-42 discusses the advantage of the stress test approach as using WGEN to “construct physically realistic and spatially coherent daily gridded weather patterns driven by well understood weather regimes and the transitions between weather regimes”. Section 5.5 needs major revisions to more clearly explain how WGEN is used to develop the stress test. Particularly confusing is whether the stochastic weather generator based on weather regime is used to generate synthetic weather for the stress test to create the system response surfaces.

Charge question 2

Does the procedure apply rational and defensible evidence for the steps taken and techniques used to capture the probability of projected changes related to climate and sea level rise? Why or why not?

The new approach developed to generate future climate scenarios makes use of the daily maximum and minimum temperature and daily precipitation that are statistically downscaled using the LOCA2 method from the CMIP6 multi-model ensemble and further bias corrected. Downscaling and bias correction are important to produce more realistic climate information, as the CMIP6 models with typical spatial resolution of ~100 km cannot resolve the regional climate of the topographically diverse California state. LOCA2 data were only available for 15 GCMs at the time of the project development. Hot models (except for those that have multiple initial conditions variants) and other models with only one variant were excluded, resulting in a total of 11 GCMs with multiple SSP scenarios for use in generating future climate scenarios. The temperature and precipitation data were spatially averaged to an aggregated value for the full CalSim 3 domain by weighting their averages over watersheds within the CalSim 3 domain by each watershed's contribution to Delta outflow. Climate change signal was then estimated by fitting linear trend lines to 30-year rolling window averages and for each GCM and SSP scenario, an average linear trend was obtained by averaging the linear trends across the initial condition variants to reduce the influence of natural variability on estimating the secular trends induced by anthropogenic forcing. A bivariate Gaussian PDF was then fitted to the temperature and precipitation changes derived from the 11 GCMs with multiple SSP scenarios. These steps (GCM selection, spatial aggregation, trend estimation and ensemble averaging, and PDF construction) taken to estimate the likelihood of temperature and precipitation changes of different magnitudes spanning the values taken from 11 GCMs and 3 SSP scenarios are defensible and useful for providing risk-informed future climate scenarios for assessing risk to SWP performance.

Future scenarios of sea level rise (SLR) were informed by the Sweet et al. 2022 sea level rise technical report. More specifically, SLR scenarios were selected from six global mean sea level (GMSL) scenarios (observation extrapolation, low, intermediate-low, intermediate, intermediate-high, and high) to align with the system risk informed level of concern. The selected scenarios were further adjusted to align with existing CalSim 3 sea level rise ANNs with SLR projections, resulting in only two SLR scenarios of 0.98 ft for the 75th and 95th percentile level of concern scenarios and 0.49 ft for the 50th percentile level of concern scenario. These steps taken to select SLR scenarios are defensible considering the compromise that needs to be made to avoid the resource intensive task of developing new ANNs for more specific SLR scenarios.

Charge question 3

Do the new scenarios provide enhanced information for water users about potential future conditions and system reliability risks? If not, why?

Compared to the previous top-down and bottom-up approaches, the hybridized approach to develop future climate scenarios provides enhanced information for water users about potential future conditions and system reliability risks. First, uncertainty in future temperature and precipitation changes is encapsulated by a simple bivariate gaussian PDF. Although fitting the projected changes from multiple GCMs and multiple SSP scenarios by a bivariate gaussian PDF is simplistic, such a PDF provides succinct information about climate uncertainty and can be used to generate a large number of future climate scenarios with attached likelihoods by randomly drawing from the PDF (e.g., Figure 5-11 shows 10,000 samples drawn from the PDF) for any hazard modeling besides SWP performance that requires temperature and precipitation scenarios. Second, the future climate scenarios can be combined with the system response surface created by stress testing the system to determine the specific temperature and precipitation changes for different levels of concern. These changes are then applied to the historical meteorological data to produce future scenarios that follow the wet and dry years in the historical record to allow evaluation of historical droughts under the future conditions. These climate scenarios that are linked to the system performance can then be further used to evaluate the system response to the combined effects of climate change (temperature and precipitation changes) and SLR. These future climate scenarios meet the three characteristics requested from the State Water Contractors as listed on page 5-3.

Charge question 4

Is this procedure an improvement over other previously used approaches to climate scenario selection/development? Why or why not?

The new procedure represents an improvement over the top-down and bottom-up approaches previously used to develop climate scenarios: (1) The new approach provides uncertainty information through the bivariate gaussian PDF, which is an improvement compared to the scenarios developed using the top-down approach which are very sensitive to the GCM model selection. (2) The new approach connects the future climate scenarios with the system performance, allowing the selection of a few climate scenarios corresponding to specified levels of concern. This is an improvement over the bottom-up approach which produces a large number of future climate scenarios that are difficult to feed into downstream planning models. The new approach is particularly useful for climate risk assessment, which requires the use of future climate scenarios to address both the consequences and the probability of climate change signals.

Charge question 5

Are there specific investigations or improvements that should be undertaken in future updates of this approach or use of this procedure to develop additional scenarios at time periods further into the future?

The new hybridized approach is well designed, makes good use of available downscaled CMIP6 data from LOCA2, and meets the requests of the users. For future updates of this approach, several areas of investigations or improvements should be considered.

1. Although the LOCA2 data are available at 3 km resolution, ultimately the climate data were aggregated to watershed level and further averaged by weighting the watershed level data to the CalSim 3 region, which covers nearly 40 million acres. These procedures reduced the impact of the fine-scale climate information from LOCA2, which were partly justified because GCMs tend to show rather different spatial patterns of change. Hence ultimately only temperature and precipitation changes averaged over the CalSim 3 region were used to scale the historical meteorological data to produce spatially distributed future climate scenarios. This begs the question of whether using LOCA2 data adds substantial value to the development of the future climate scenarios, considering that the number of GCMs selected from CMIP6 was limited by the availability of LOCA2 data. The limited number of GCMs with multiple variants and SSP scenarios had likely impacted the fitting of the bivariate gaussian PDF to represent scenario uncertainty. In contrast, direct use of GCM output with simple bias correction can maximize the use of the CMIP6 multi-model ensemble and the multi-model large ensemble simulations for scenario development. Analysis investigating this option and comparing the results with the current method may guide the design of climate-risk climate scenarios development in the future.
2. Since the use of LOCA2 data limited the number of CMIP6 GCMs that could be included in the scenario development, the resulting bivariate gaussian PDF was constructed by combining the temperature and precipitation

changes simulated by different GCMs for different SSP scenarios. If future work can maximize the use of the CMIP multi-model ensemble and multi-model large ensemble simulations (e.g., as discussed above), it would be more useful to develop scenarios and PDFs separately for each SSP scenario. This way users of the climate scenarios may select specific SSP scenarios or apply weighting to these scenarios for their own assessment. By providing PDFs and temperature and precipitation perturbations separately for each SSP, users may evaluate how different climate mitigation strategies represented by the SSP scenarios may affect their system performance.

3. In the current approach, temperature and precipitation changes were calculated as annual mean changes for stress testing the system as well as generating future climate scenarios for VIC and CalSim 3 modeling. Since the regional climate of California exhibits strong seasonality, with meteorological changes during the cold season affecting water availability in the summer, it is important to consider developing future climate scenarios using monthly rather than annual mean temperature and precipitation changes. An interesting aspect of climate change over California is the sharpening of the precipitation seasonal cycle, with increased precipitation during winter and reduced precipitation during fall and spring, which has been robustly projected across the CMIP multi-model ensembles (Swain et al. 2018; Dong et al. 2019a). Dong et al. (2019b) further found that the seasonal cycle of extreme precipitation in California is also projected to sharpen, as the frequency of atmospheric rivers making landfall in the region will increase in winter and decrease in fall and spring. Such seasonality changes for the mean and extreme precipitation could have important implications for managing water resources, which cannot be captured by annual mean precipitation changes. Given that users of the climate scenarios selected the 8RI Apr-Jul as a useful performance metric, and the April-July water availability could be quite sensitive to the precipitation seasonality changes, future work should consider this factor, which drives the need for climate scenarios with monthly changes.
4. As noted in chapter 6 (Limitations), the authors have already identified the need to improve CalSim 3 modeling using sub-monthly time step to model the impact of extreme precipitation and runoff on operations. This is an important aspect for improvements in the future as increases in the frequency and intensity of extreme precipitation and runoff events are

robust changes supported by theory and climate models under global warming.

5. With water availability being one of the important performance metrics of the system, it’s important to consider changes in the water budget that influence seasonal runoff amount. Increasing CO2 in the atmosphere has important effects on evapotranspiration through changes in plant water use efficiency (i.e., CO2 effect on stomatal conductance). This is an important consideration for future modeling work to account for changes in water availability related not only to changes in precipitation and temperature but also changes in evapotranspiration, with implications for drought (e.g., Swann et al. 2017).
6. In the risk-informed climate scenarios development approach documented in the report, changes in temperature and precipitation, including the 7% $^{o}C^{-1}$ scaling applied to extreme precipitation, are used to perturb the historical daily temperature and precipitation to generate future scenarios. While this approach allows the users to consider how historical events such as drought may unfold in the future, these scenarios do not fully account for changes in the probability of extreme events, which is an important aspect of risk assessment. The stochastic weather generator provides an opportunity to develop synthetic climate scenarios that can reflect changes in both intensity and frequency of extreme events in a more holistic storyline framework in which not only the thermodynamic influence of global warming is accounted for but dynamical influence can be incorporated based on atmospheric circulation changes simulated by GCMs. For example, analysis of GCM simulations may identify groups of models featuring robust changes in certain weather regimes. Such changes can be reflected in the stochastic weather generator to produce scenarios consistent with the circulation changes simulated by the GCMs. Developing scenarios that account for both thermodynamic and dynamical changes will require methodological development, but it offers a broader range of climate scenarios for climate risk analysis. Such effort should be pursued as part of longer-term planning, potentially in collaboration with academic and laboratory partners.

References

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