Final Project Report
Southwest Climate Adaptation Science Center (SW CASC)

SECTION 1. ADMINISTRATIVE INFORMATION

Project title	Understanding the Effects of Seasonal Precipitation Timing Changes on Hydrology and Ecosystems in the Colorado River Basin
Agreement number	G23AC00684-00/G18AC00320
Award recipient agency/institution	Scripps Institution of Oceanography, University of California, San Diego
Principal Investigator (PI)	Rachel E. S. Clemesha, Scripps Institution of Oceanography, UC San Diego (rclemesha@ucsd.edu; 858-900-1639)
Co-Investigators	Erica Fleishman (Oregon State University); Sasha Gershunov (Scripps Institution of Oceanography, UC San Diego)
Other key project personnel / collaborators	Kristen Guirguis; Gabrielle La Rochelle; Rosa Luna-Niño; Tereza Cavazos; Bradley Udall; Seth Shanahan
Host institution (SW CASC)	Aaron Lien, SW CASC Director, University of Arizona (alien@arizona.edu)
Report date	Jan. 28, 2026
Project period covered in this final report	Oct. 1, 2023 to Sep 30, 2025
Actual Total Cost	UCSD/Scripps $136,623, University of Arizona $13,375, Total $149,998

SECTION 2. PUBLIC SUMMARY

Precipitation seasonality, the timing of rainfall and snowfall across the year, strongly influences water supply, ecosystem health, wildfire risk, and agricultural productivity across the western United States. This project evaluated how well global climate models represent observed precipitation seasonality and how projected changes in seasonality may affect climate risk assessments in the Southwest, including the Colorado River Basin and broader western US.

A key challenge, which our work uncovered, is that commonly used downscaled climate products can obscure important biases in the underlying global models. To address this, we developed and applied a “seasonality realism error” metric that quantifies how closely each climate model reproduces the observed month-to-month distribution of precipitation. We then compared future projections from models with realistic seasonality against projections from models with substantial seasonal timing errors.

We find that many models reproduce seasonality reasonably well in much of the West, but performance is notably weaker in regions influenced by the North American Monsoon. In the Southwest, projected future changes in summer precipitation seasonality are highly uncertain, and part of that uncertainty stems from model deficiencies that can be hidden by downscaling. By explicitly identifying and separating higher-skill models from deficient models, this work provides a more defensible basis for interpreting projected changes in precipitation timing and for communicating uncertainty to water and land managers.

SECTION 3. PROJECT SUMMARY

This project assessed historical precipitation seasonality and future changes across the western United States, which have implications for hydrology and ecosystems. The work emphasized careful treatment of climate model biases in timing or precipitation, including biases that are not apparent in statistically downscaled products.

Approach: We analyzed observational precipitation datasets and ensembles of sixth phase Coupled Model Intercomparison Project (CMIP6) model simulations (both raw before any bias-correction and LOCA2 downscaled products). A Kullback–Leibler divergence-based seasonality realism error metric was used to quantify each model’s ability to reproduce the observed annual precipitation cycle. Models were classified as “skillful” or “deficient” by climate division using a consistent error threshold.

Key results: Across much of the West, models simulate precipitation timing with relatively high realism. However, the monsoon-influenced Southwest shows the largest seasonal timing deficiencies, including delayed monsoon onset and biases in peak-season precipitation. These deficiencies can materially influence the interpretation of future precipitation seasonality changes in the Southwest.

Primary product: A peer-reviewed manuscript documenting the method and findings has been updated and submitted; it is currently under review at Environmental Research: Climate.

Clemesha, R. E. S., Guirguis, K., Luna-Niño, R., Weyant, A., Gershunov, A., Cayan, D. R., Fleishman, E., Cavazos, T., Udall, B., & Shanahan, S. (under review). *Assessing future changes in precipitation seasonality across the western United States by explicitly dealing with climate model biases hidden by downscaling*. Environmental Research: Climate.

SECTION 4.

4.1 Purpose and Objectives

The overarching purpose of the project was to improve understanding of how the timing of precipitation across seasons may change under climate change and to evaluate the consequences of those changes for hydrology and ecosystems in the Colorado River Basin and the broader Southwestern United States.

Original project objectives and goals included:

(1) To analyze historical and future projections of temperature and precipitation, including contributions from the North American Monsoon (NAM).
(2) To assess the consequences of precipitation changes on vegetation, wildfire dynamics, and habitat for wildlife.
(3) To improve operational decision-making and inform management of water and other natural resources in the context of climate change.

No significant changes were made to the original proposal. Some changes were made as to which aspects of the objectives were prioritized or possible given the limitations of global climate models and remote-sensing of interannual variability in our selected vegetation coverage. We uncovered and reported on these limitations in Clemesha et al. (Under Review) and La Rochelle, 2025 (MS dissertation advised by Co-I Fleishman, "Harmonic Analysis of NDVI for Phenology-Based Detection of Cheatgrass (*Bromus tectorum*) in the Great Basin"), respectively. In particular, (A) the lack of skill of many climate models in correctly simulating the seasonality of historical precipitation in locations impacted by the North American Monsoon and (B) the remote-sensing challenges to accurate mapping of annual presence and abundance of *Bromus tectorum* (cheatgrass) limited the work that could be done on objective (2) to assess the consequences of precipitation change. We did find that in the Upper Colorado River Basin, winters may become wetter but springs drier. Culling of deficient models suggests increases in summer and early autumn precipitation in areas of Arizona, New Mexico, and Utah, including parts of the upper and lower Colorado River Basin. These changes are likely to affect both natural and human systems. For example, drying springs have been identified as a driver of observed Upper Colorado River streamflow declines (Hogan and Lundquist, 2024), and our work is consistent with other indications that spring drying likely will continue into the future.

4.2 Organization and Approach

The project team coordinated via regular meetings and iterative analysis and writing. The workflow was designed to (1) characterize observed precipitation seasonality, (2) quantify model skill in representing the annual precipitation cycle, and (3) interpret future seasonality changes while explicitly accounting for model deficiencies.

Major research tasks and methods:

- Observed climate analysis: evaluate the historical seasonal cycle and interannual variability of precipitation across climate divisions and subregions relevant to the Southwest.
- Model evaluation: compute a seasonality realism error (SRE) metric for CMIP6 models using a Kullback–Leibler divergence formulation applied to long-term monthly mean precipitation distributions.
- Future projections: compare projected changes in precipitation seasonality for models classified as skillful versus deficient, highlighting regions where model bias strongly affects interpretation.

- Downscaling context: use LOCA2 downscaled precipitation as supporting analysis to demonstrate that downscaling may mask underlying GCM seasonality deficiencies.

Management partner engagement:
The team engaged with decision-makers including the Southern Nevada Water Authority and members of the Colorado River Climate and Hydrology Work Group. Clemesha et al. (Under Review) was co-produced with Seth Shanahan of the Southern Nevada Water Authority.

4.3 Project Results, Analysis and Findings

The primary analytical and scientific outcome of this project is documented in the submitted manuscript: Clemesha et al., "Assessing future changes in precipitation seasonality across the western US by explicitly dealing with climate model biases (hidden by downscaling)" (under review, Environmental Research: Climate).
Key results include:

- A model-evaluation framework: A Kullback–Leibler divergence-based seasonality realism error (SRE) metric quantifies how well each climate model reproduces the observed annual cycle of precipitation timing (Table 1, Fig. 1)
- Spatially heterogeneous model skill: Many models represent seasonality reasonably well across the Pacific Northwest, California coastal divisions, and interior mountain/Great Basin regions, but skill is substantially lower in the monsoon-influenced Southwest (Fig. 1)
- Southwest monsoon deficiencies: Deficient models commonly show delayed monsoon precipitation and/or biased peak-season amounts; these errors are especially consequential where summer precipitation is a smaller but societally important fraction of annual totals (Fig. 2)
- Downscaling can conceal errors: Because LOCA statistical downscaling preserves the seasonality of the training (observed) dataset and projected monthly changes of the driving GCM, a downscaled product can appear plausible (e.g. shows a realistic annual cycle of precipitation) while retaining key timing biases present in the parent global model (Fig. 3)
- Implications for projections: In monsoon-affected regions, projected future changes in summer precipitation seasonality are highly uncertain, and uncertainty can be reduced (or at least more clearly characterized) by screening models for seasonality realism. (Fig. 4).

Below we include a table and figures that support the above key results:

Model	SRE rank	WUS SRE	SRE min	SRE max	LOCA	ssp585	Resolution (deg lon x lat)
ACCESS-CM2	13	0.03	0.002	0.086	Y	Y	1.875° x 1.25°
ACCESS-ESM1-5	5	0.023	0.001	0.121	N	Y	1.875° x 1.25°
AWI-CM-1-1-MR	32	0.063	0.004	0.158	Y	Y	~0.94° x ~0.94°
BCC-CSM2-MR	29	0.05	0.002	0.205	Y	Y	1.125° x 1.125°
BCC-ESM1	28	0.05	0.004	0.175	N	N	2.8° x 2.8°
CAMS-CSM1-0	33	0.079	0.002	0.154	N	N	1.125° x 1.125°
CESM2	4	0.023	0.001	0.072	N	Y	1.25° x 0.9°
CESM2-FV2	11	0.029	0.002	0.084	N	N	2.5° x 1.9°
CESM2-WACCM	6	0.024	0.002	0.061	N	Y	1.25° x 0.9°
CMCC-CM2-SR5	10	0.029	0.002	0.145	N	Y	1.25° x 0.9°
CNRM-CM6-1	24	0.046	0.001	0.19	Y	Y	1.4° x 1.4°
CNRM-CM6-1-HR	26	0.046	0.002	0.223	N	Y	0.5° x 0.5°
CNRM-ESM2-1	30	0.052	0.002	0.204	Y	Y	1.4° x 1.4°
CanESM5	16	0.035	0.001	0.094	Y	Y	2.8° x 2.8°
EC-Earth3	15	0.033	0.002	0.19	Y	Y	0.7° x 0.7°
EC-Earth3-Veg	22	0.041	0.002	0.222	Y	Y	0.7° x 0.7°
FGOALS-f3-L	35	0.086	0.003	0.297	N	N	1.25° x 1.0°
FGOALS-g3	18	0.036	0.004	0.129	Y	Y	2.0° x ~2.25°
GFDL-CM4	19	0.036	0.001	0.103	N	Y	1.25° x 1.0°
GFDL-ESM4	23	0.043	0.001	0.139	Y	Y	1.25° x 1.0°
HadGEM3-GC31-LL	2	0.018	0.001	0.052	N	Y	1.875° x 1.25°
IITM-ESM	12	0.03	0.002	0.104	N	N	~1.875° x ~1.915°
INM-CM4-8	9	0.029	0.001	0.105	Y	Y	2.0° x 1.5°
INM-CM5-0	3	0.019	0.001	0.056	Y	Y	2.0° x 1.5°
IPSL-CM6A-LR	21	0.039	0.004	0.147	Y	Y	2.5° x ~1.27°
KACE-1-0-G	31	0.057	0.004	0.136	Y	Y	1.875° x 1.25°
MIROC6	17	0.035	0.001	0.152	Y	Y	1.4° x 1.4°
MPI-ESM-1-2-HAM	37	0.09	0.002	0.24	N	N	1.875° x 1.25°
MPI-ESM1-2-HR	34	0.083	0.003	0.246	Y	Y	0.94° x 0.93°
MPI-ESM1-2-LR	36	0.087	0.002	0.238	Y	Y	1.875° x 1.85°
MRI-ESM2-0	20	0.037	0.003	0.15	Y	Y	1.125° x 1.125°
NESM3	14	0.03	0.004	0.089	N	Y	1.9° x 1.9°
NorCPM1	27	0.05	0.005	0.13	N	N	2.5° x 1.9°
NorESM2-LM	25	0.046	0.005	0.11	Y	Y	2.5° x 1.9°
NorESM2-MM	7	0.026	0.002	0.085	Y	Y	1.25° x 0.94°
TaiESM1	8	0.028	0.003	0.131	Y	Y	1.25° x 0.94°
UKESM1-0-LL	1	0.017	0.001	0.054	N	Y	1.875° x 1.25°

Table 1: Summary of 37 CMIP6 models used, range of seasonality realism error (SRE) (across divisions), and West-wide area weighed SRE and rank.

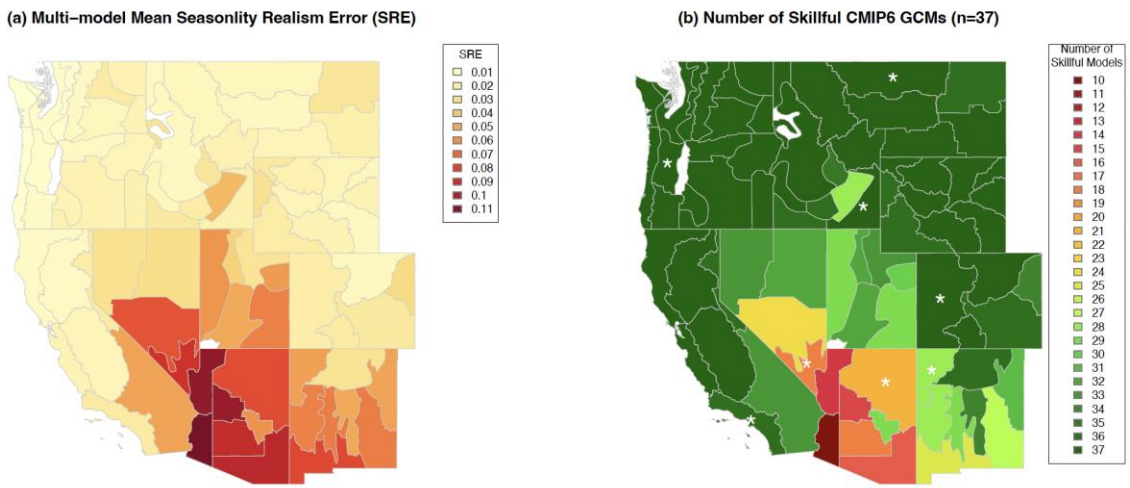

Figure 1: (a) Multi-model mean of seasonality realism error (SRE) for 37 GCMs included in CMIP6 (more skillful models have lower SRE). (b) Number of GCMs classified as skillful based on SRE. A white * marks the eight climate divisions used in other figures.

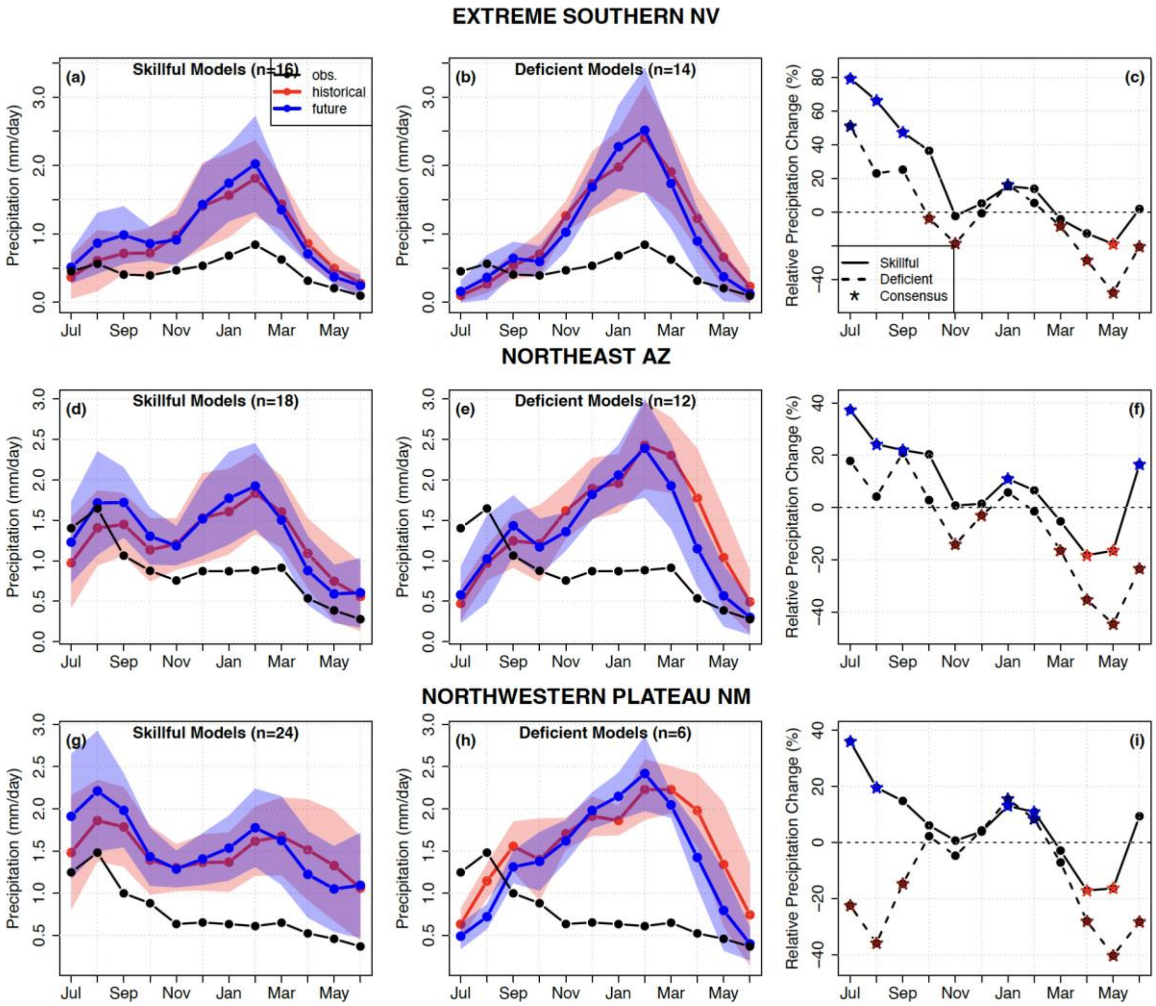

Figure 2: Left and middle: Observed (black), modeled historic (red), and future (blue) monthly mean precipitation in mm/day. Envelopes show +- 1 standard deviation for 30 models. Right: Monthly percentage of relative change in multi-model mean precipitation [(future – historic)/historic]. Asterisks indicate that at least 70% of the models agree on the sign of the change (red, decreasing; blue, increasing). Deficient models (middle) were identified and are shown in contrast to the skillful model (left).

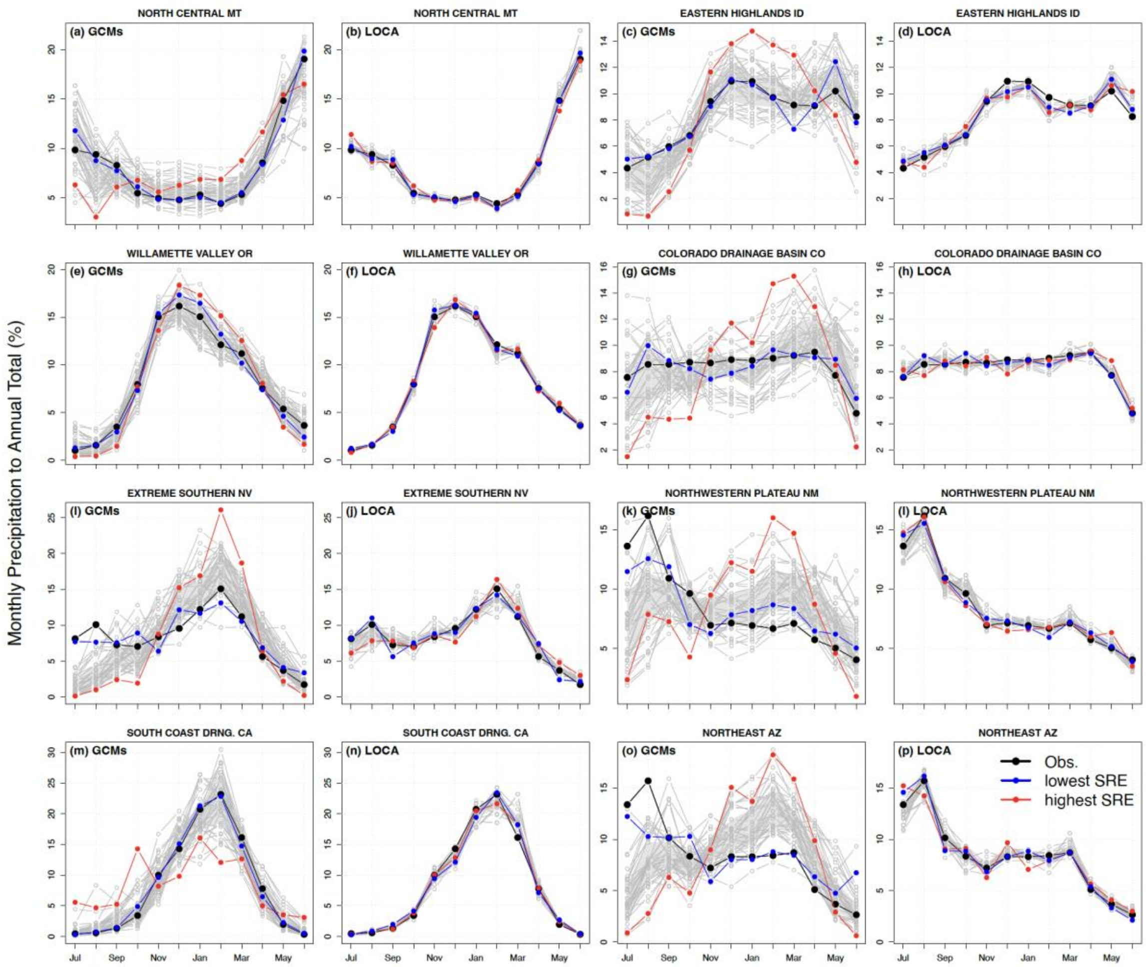

Figure 3: Monthly precipitation contribution to annual total (1950-2014) from observations (black), GCMs (first and third columns) and LOCA bias corrected output (second and fourth columns) in eight representative climate divisions throughout the western United States. Gray traces denote each model's annual cycle (n =37 for GCMs, n = 21 for LOCA). The most skillful models (lowest SRE) are in blue and the most deficient models (highest SRE) are in red. For direct comparison from GCM to LOCA, the most and least skillful models are identified in the 21-model subset. Gray envelope denotes the 25th to 75th percentile of model outputs.

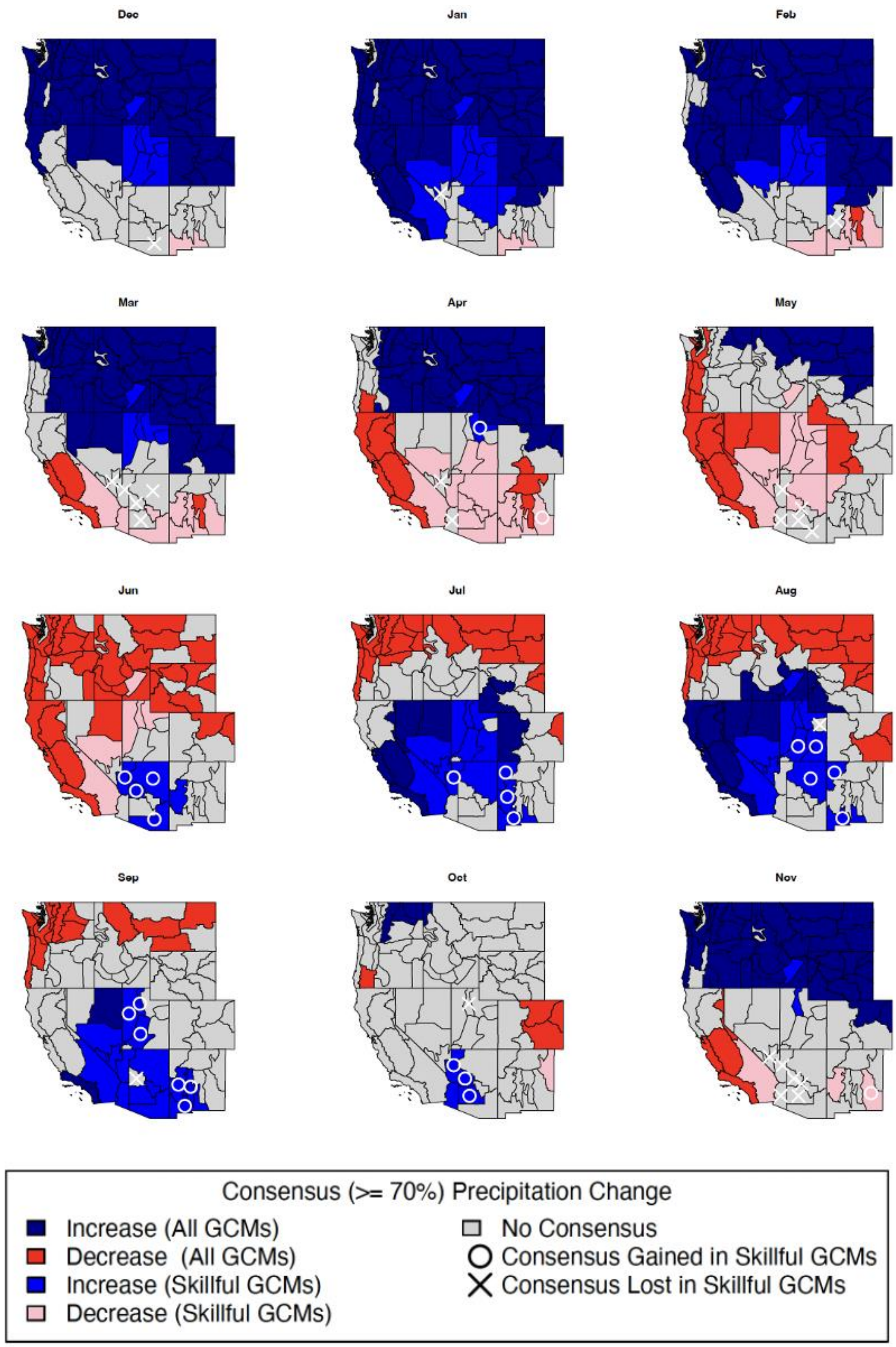

Figure 4: Consensus increases (blues), consensus decreases (reds), and no consensus (gray) in modeled monthly precipitation from 1950 - 2014 to 2051 - 2100. Xs indicate loss, and circles indicate gain of consensus when only skillful models are considered. Dark red and blue are used for divisions with no deficient models (i.e. all GCMs deemed

skillful). For divisions with deficient models, consensus (or lack of) is shown for only skillful models.

Additionally, detailed findings regarding tracking cheatgrass (a non-native annual grass that creates a layer of fine fuels) with remote sensing are reported in La Rochelle, 2025 (MS dissertation advised by Co-I Fleishman, “Harmonic Analysis of NDVI for Phenology-Based Detection of Cheatgrass (*Bromus tectorum*) in the Great Basin”). Briefly, cheatgrass is identifiable with data from satellite imagery due to its phenology, which is distinct from that of most native vegetation. Cheatgrass greens up in spring, when most native species are dormant, and senesces in early to mid-summer, when most native vegetation is still photosynthetically active. Nevertheless, interannual variability in the distribution and density of cheatgrass is a challenge to accurate mapping of the species’ annual presence and abundance.

Reflectance of cheatgrass can vary substantially among years and can erroneously appear to indicate land-cover change. Most land-cover classification algorithms rely on single-year reflectance or average reflectance throughout phenological cycles to differentiate among land-cover types, and therefore fail to capture interannual variability. Another challenge in remote sensing of cheatgrass is the lack of field data. Although there are many accounts of cheatgrass presence within the Intermountain West over decades, there are not enough environmentally stratified samples of cheatgrass in single years over large areas to capture the variability of cheatgrass among years. Classification models have been trained on records of cheatgrass presence and absence that were pooled over multiple years, but doing so does not account for interannual variability in cheatgrass extent or abundance. Moreover, cheatgrass is only distinguishable during green up and senescence, from spring to mid-summer. A sensor with a short return interval would yield the greatest volume of data for capturing cheatgrass phenology. However, sensors with short return intervals typically capture coarse-resolution images.

We evaluated the effectiveness of a harmonic-based classifier trained on field data for classifying cheatgrass presence in 2013 and 2023. Results indicated limitations in model transferability among years. Given the influence of climate change on precipitation patterns and cheatgrass abundance, annual calibration may be necessary to maintain classification accuracy. Collection of annual field data likely will enhance classification reliability.

4.4 Conclusions and Recommendations

This project demonstrates that climate model biases in precipitation seasonality are both regionally specific and practically important. The seasonality realism error framework provides a method for separating more realistic models from deficient models, improving interpretation of projected hydroclimate change.

As mentioned in Section 4.1, the lack of skill of many climate models in correctly simulating the seasonality of historical precipitation in locations impacted by the North American Monsoon, and the remote-sensing challenges to accurate mapping of annual presence and abundance of *Bromus tectorum* (cheatgrass), limited the proposed work that could be completed on objective (2) to assess the consequences of precipitation change on vegetation, wildfire dynamics, and habitat for wildlife.

Recommendations for scientific and management use:

- When assessing future precipitation timing in the Southwest, explicitly evaluate model skill in representing the observed annual cycle; do not rely solely on downscaled products.
- Communicate monsoon-related uncertainty clearly: projections of summer precipitation timing and amount in monsoon-influenced regions remain highly uncertain and sensitive to model deficiencies.
- Prioritize improved representation of the North American Monsoon in climate modeling and evaluation frameworks, as this is a key limiting factor for actionable projections in the Southwest.

4.5 Outreach and Products

Manuscript submitted for peer-review:
Clemesha, R. E. S., Guirguis, K., Luna-Niño, R., Gershunov, S., Fleishman, E., Cavazos, T., Udall, B., and Shanahan, S. Assessing future changes in precipitation seasonality across the western US by explicitly dealing with climate model biases (hidden by downscaling)., Submitted, and currently under review at Environmental Research: Climate.
Submission date and manuscript ID: Dec. 12, 2025, ERCL-100917

Data availability (planned): UC San Diego Library Digital Collections (dataset record to be finalized at time of publication). Clemesha, Rachel E. S.; Guirguis, Kristen; Luna-Niño, Rosa; Weyant, Alexander; Gershunov, Alexander; Cayan, Daniel R.; Fleishman, Erica; Cavazos, Tereza; Udall, Bradley; Shanahan, Seth (2025). Data from: Assessing future changes in precipitation seasonality across the western US by explicitly dealing with climate model biases (hidden by downscaling https://doi.org/10.6075/J0MP5482

Project-related briefings, presentations, and stakeholder communications:

- 4 April 2024: Briefing with Seth Shanahan, Southern Nevada Water Authority (virtual).
- 18 April 2024: Briefing with the Colorado River Climate and Hydrology Work Group (virtual; stakeholders from Central Arizona Project, Colorado Water Conservation Board, and others).
- 9 Dec 2024: AGU Fall Meeting, Washington D.C., oral presentation, "History and Future Projections of the Diverse Seasonalities of Precipitation within the Colorado River Basin and Southwestern United States"

- 18 Apr 2025: SW CASC, USDA, & CLIMAS -webinar, Changes In Precipitation In The Southwestern United States, for the public, resource managers, “The Diverse Seasonalities of Precipitation within the Southwest”
- 22 Apr 2025: Del Mar Climate & Sustainability Series — Earth Day talk, for community members “From Storms, Marine Layer Clouds & Extreme Heat to Santa Ana Winds”
- 30 May 2025: National Weather Service, San Diego Forecast Office, Operational Forecasters
- 23 Sep 2025: Presentation to Western Regional Partnership meeting focused on water security in the Colorado River
- 22 Oct 2025: Virtual attendee and participant, Colorado River Climate and Hydrology Work Group Seminar Webinar