

Supplementary Material

Observed and Projected Monthly Precipitation Distribution Shifts as Hydroclimatic Indicators for Regional Water-Resource Assessment Using PRISM and NEX-GDDP-CMIP6

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This supplementary material provides additional figures and tables supporting the observed PRISM analysis, CMIP6 projected changes, selected-model spread assessment, supplementary sensitivity analyses, and revision-added historical model-evaluation, hypothesis-testing, and hydroclimatic screening diagnostics.

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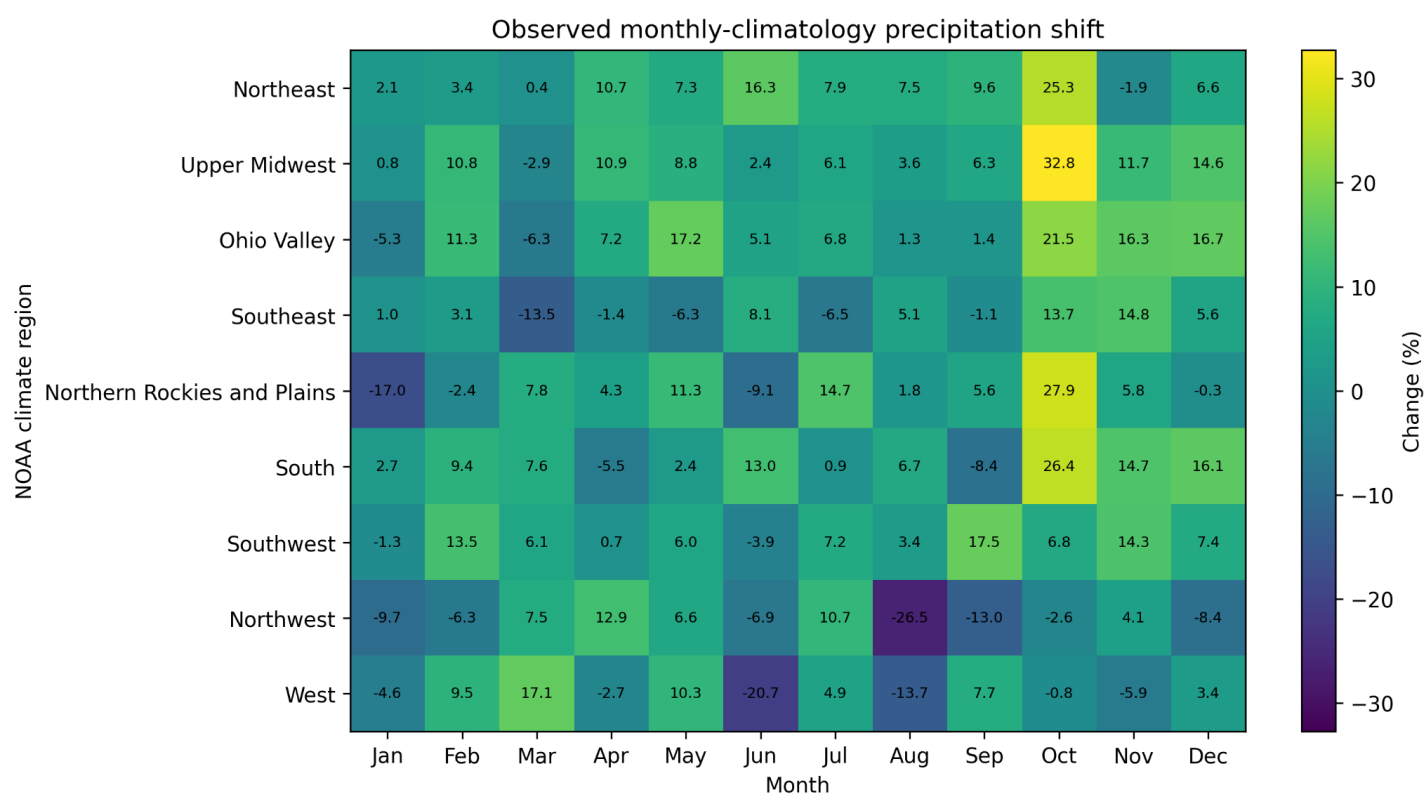


Figure S1. Observed monthly climatology precipitation changes between 1941-1980 and 1981-2020 across NOAA Climate Regions. Values indicate percentage changes in monthly climatological precipitation.

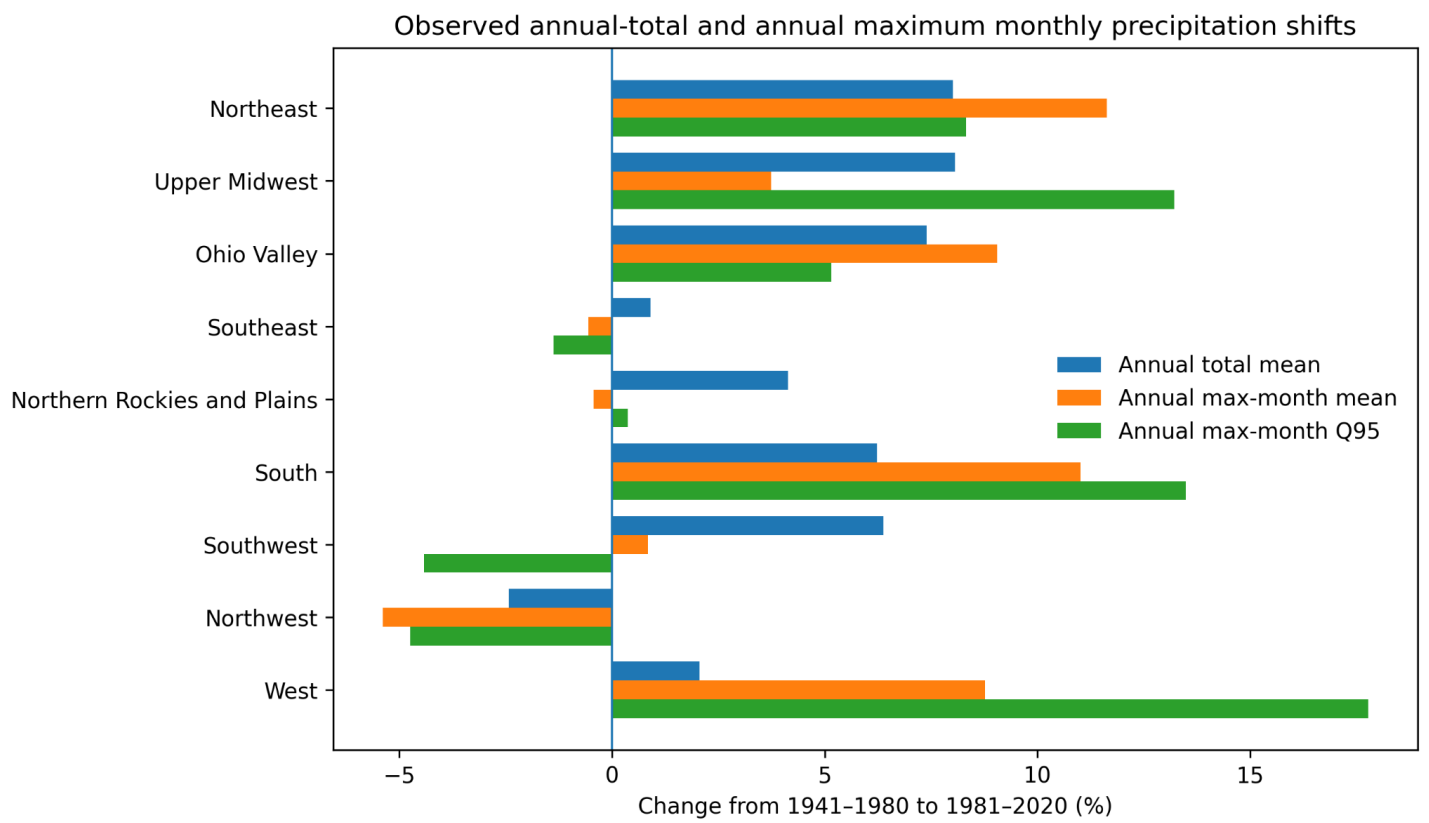


Figure S2. Observed changes in annual total precipitation and annual maximum monthly precipitation between 1941-1980 and 1981-2020.

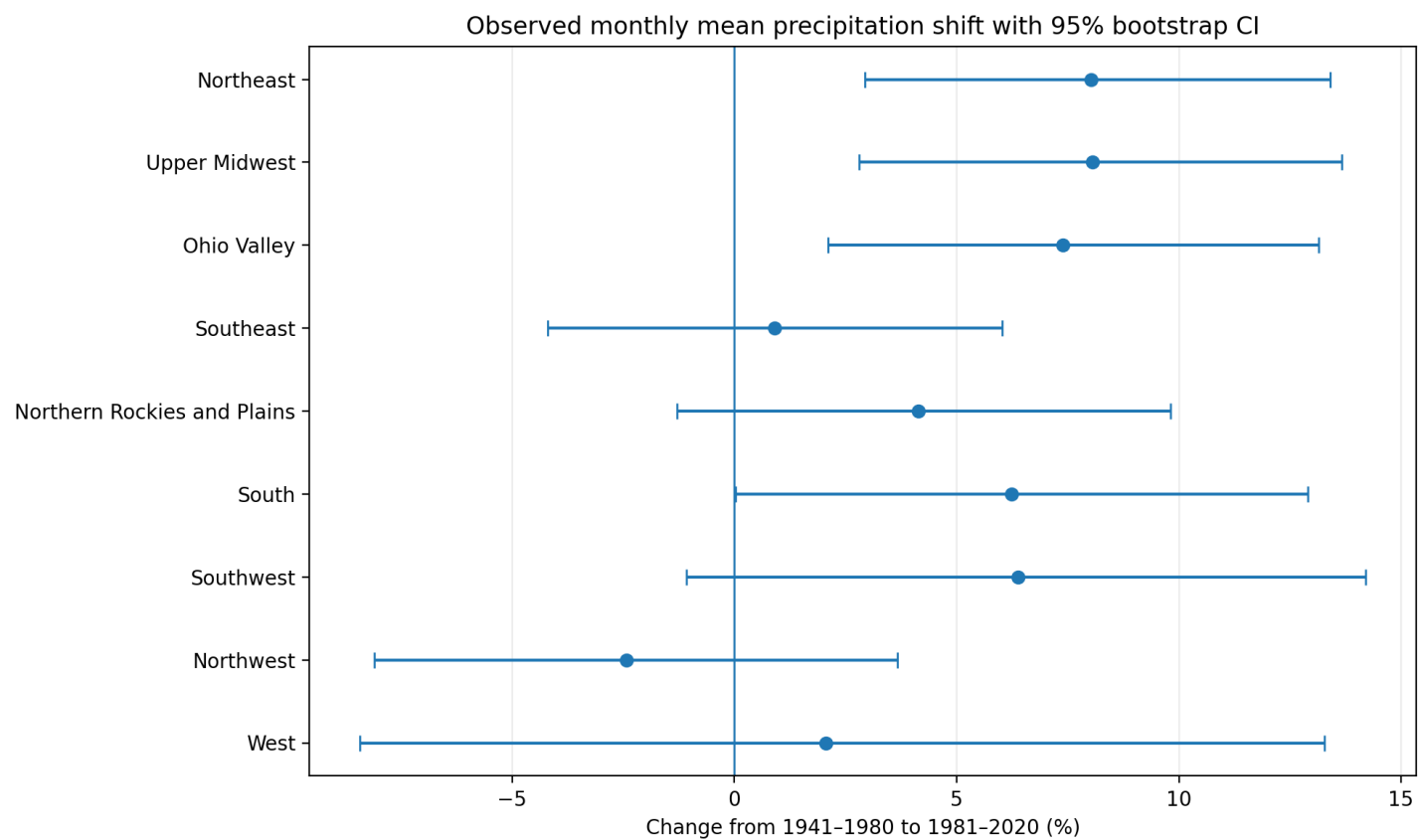


Figure S3a. Bootstrap confidence intervals for observed changes in mean monthly precipitation.

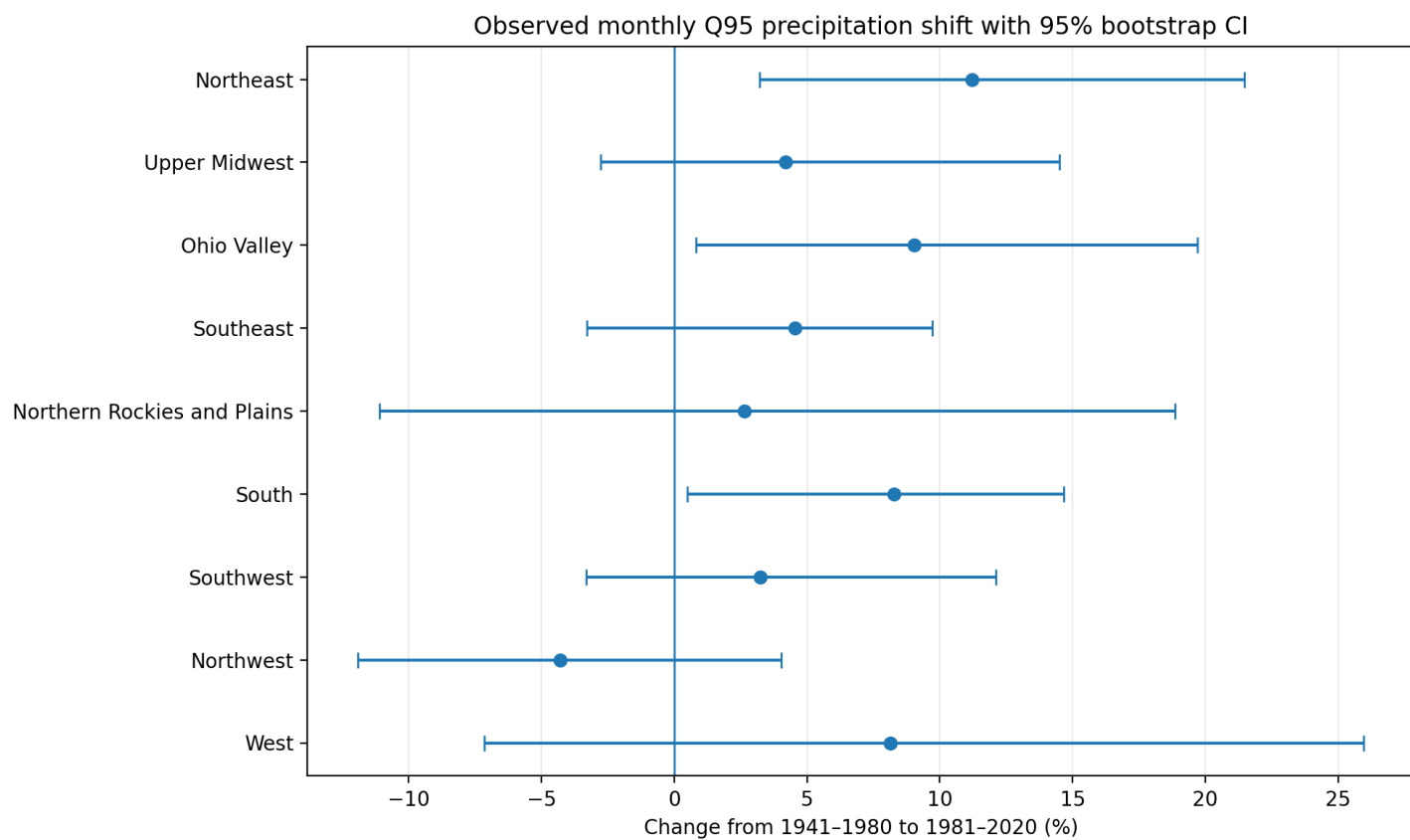


Figure S3b. Bootstrap confidence intervals for observed changes in monthly Q95 precipitation.

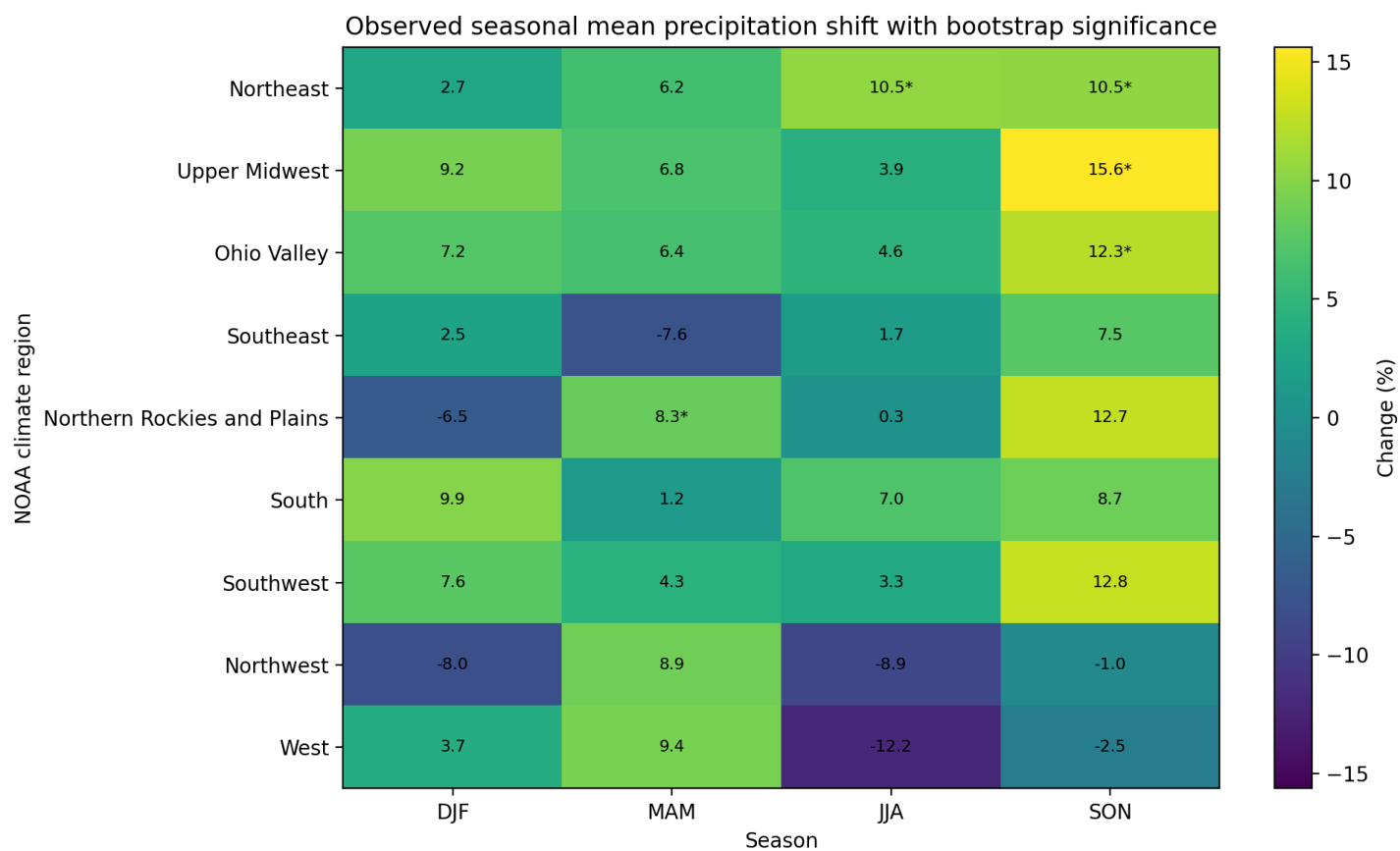


Figure S3c. Observed seasonal mean precipitation changes with bootstrap robustness indicators.

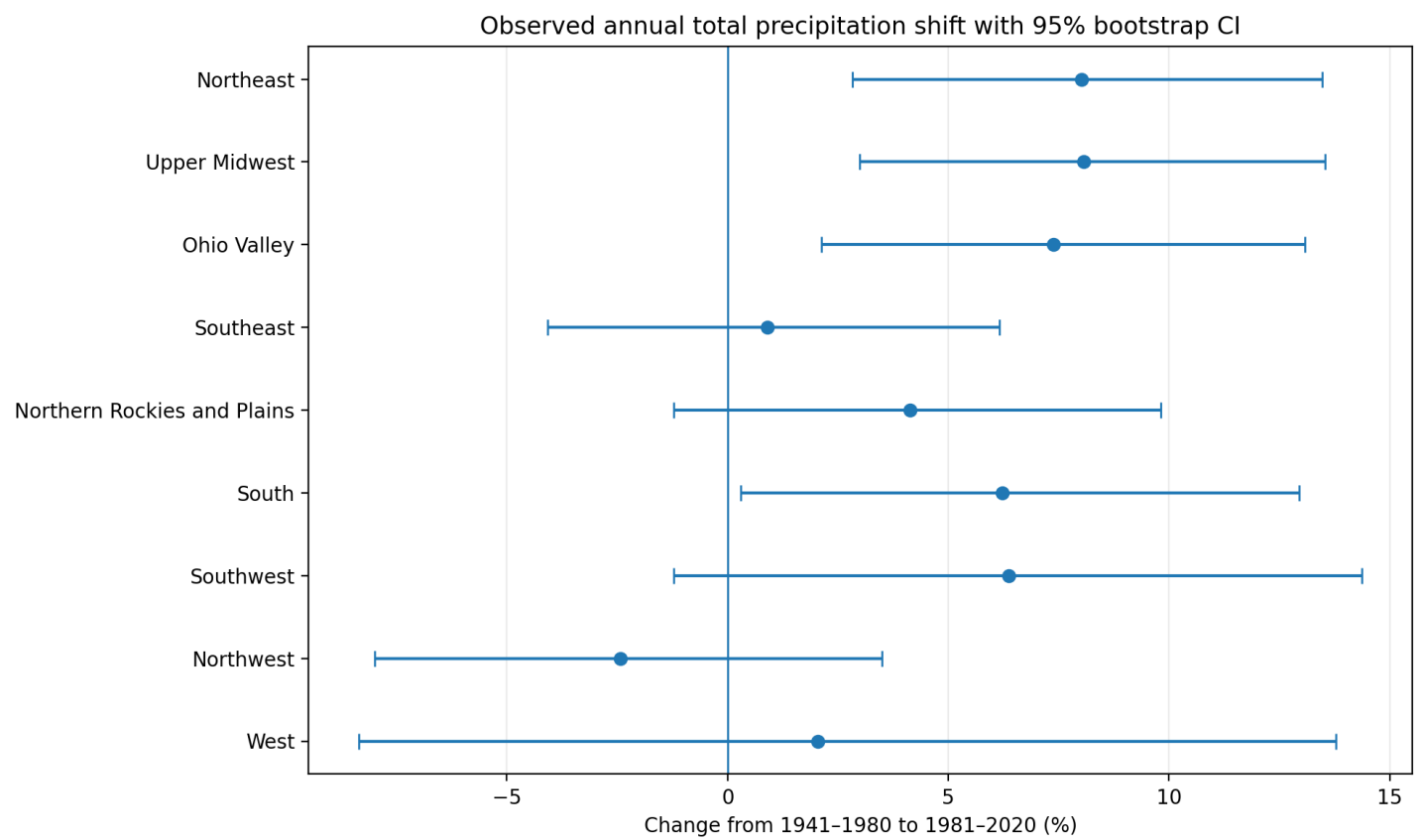


Figure S3d. Bootstrap confidence intervals for observed changes in annual total precipitation.

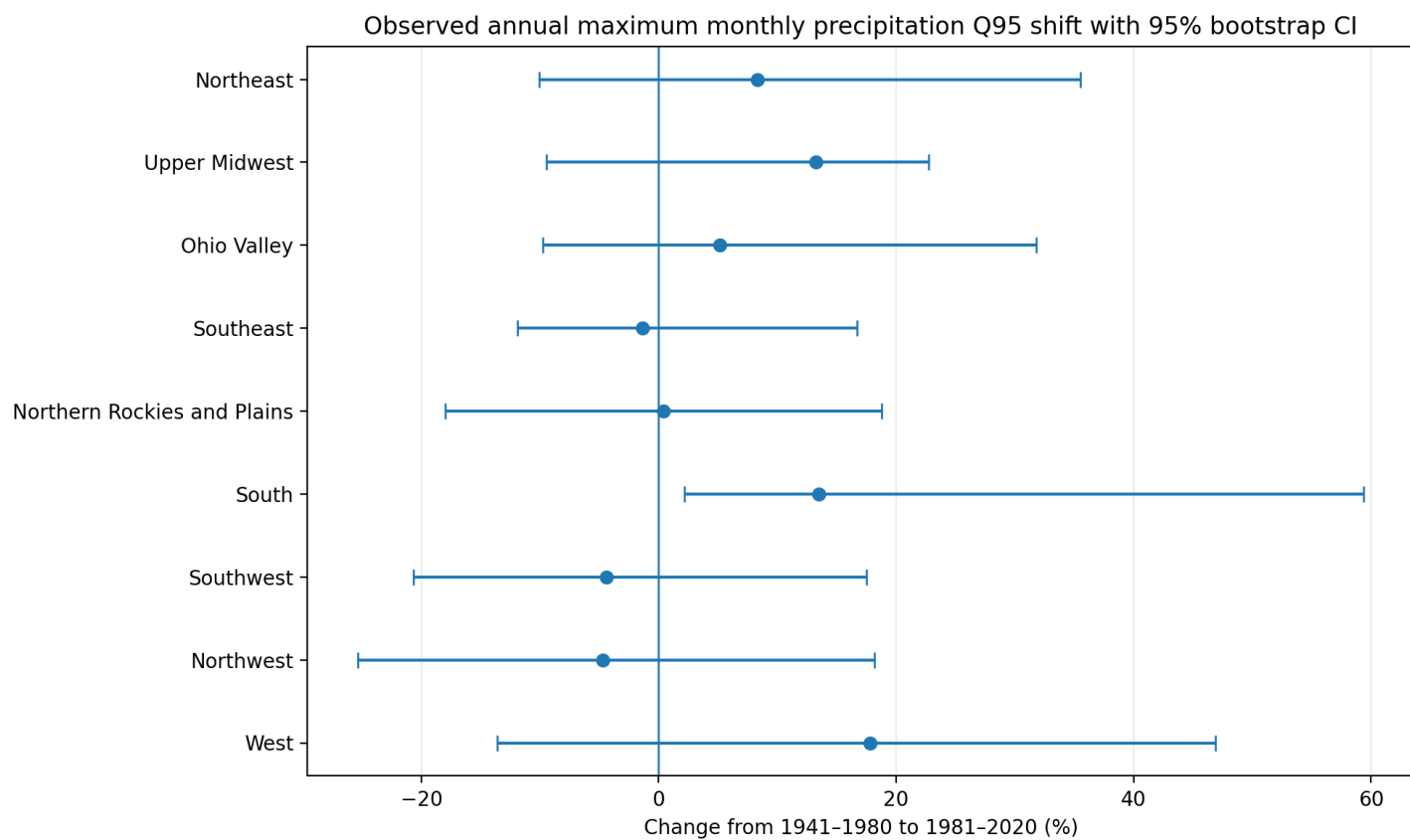


Figure S3e. Bootstrap confidence intervals for observed changes in annual maximum monthly Q95 precipitation.

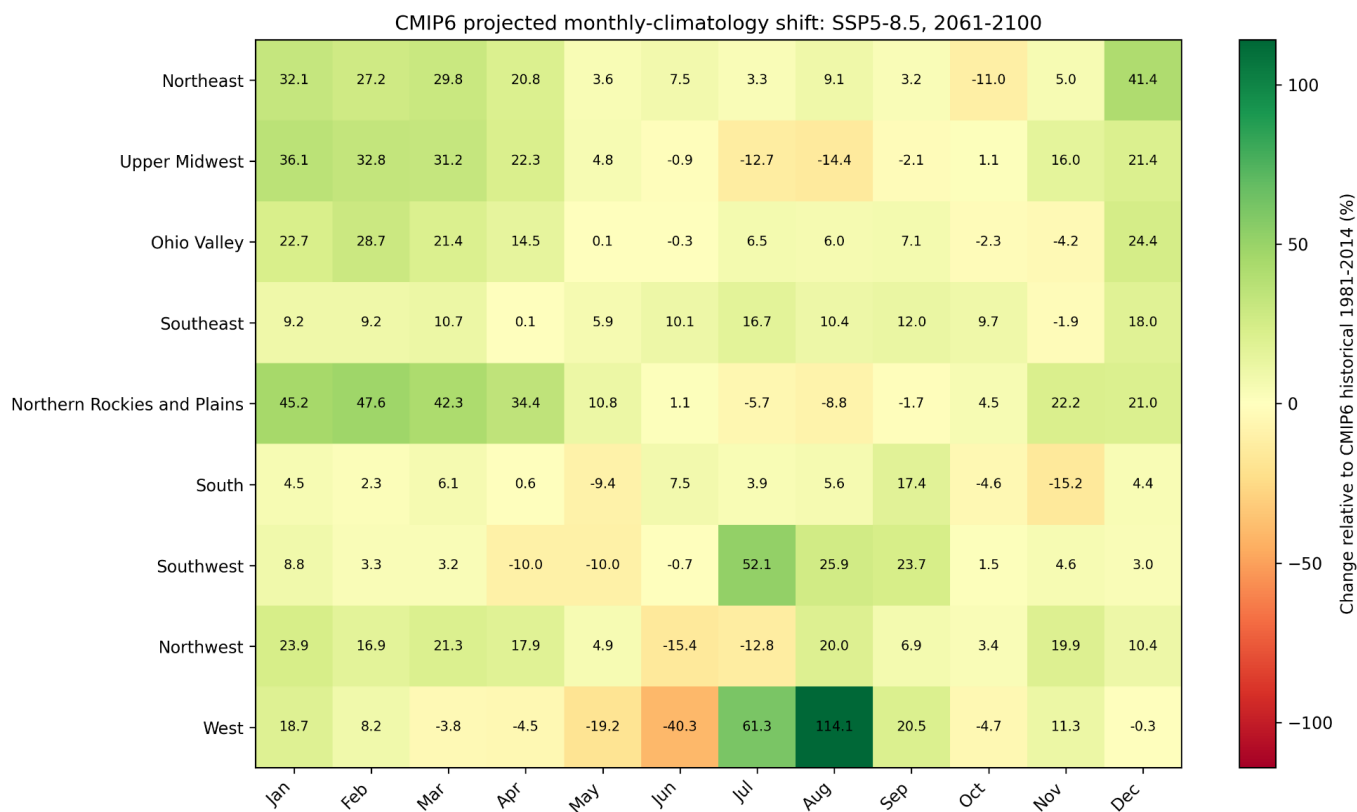


Figure S4. CMIP6 ensemble-median monthly climatology precipitation changes under SSP5-8.5 during 2061-2100 relative to each model historical 1981-2014 reference period.

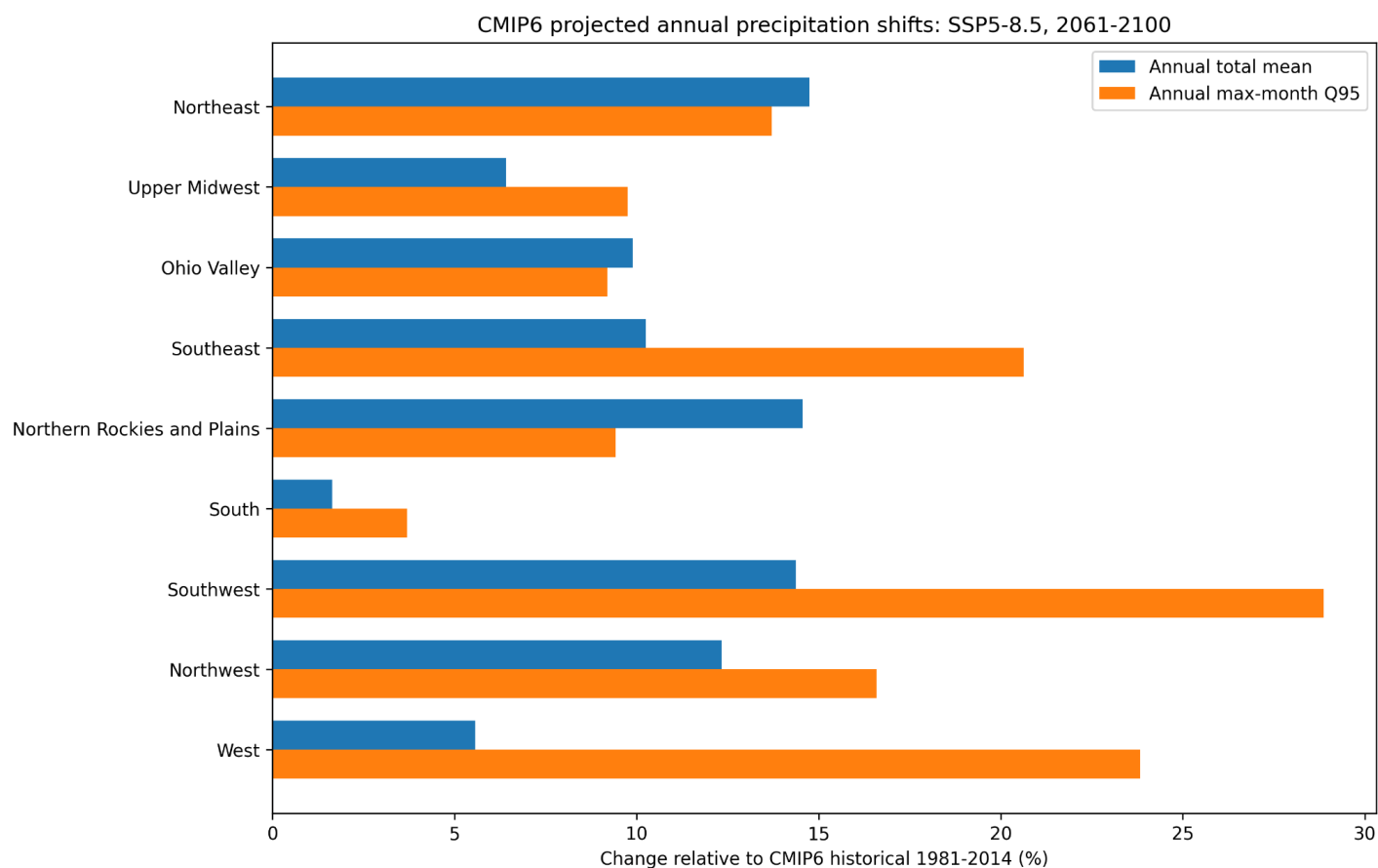


Figure S5. CMIP6 ensemble-median changes in annual total precipitation and annual maximum monthly precipitation under SSP5-8.5 during 2061-2100.

Additional sensitivity analyses

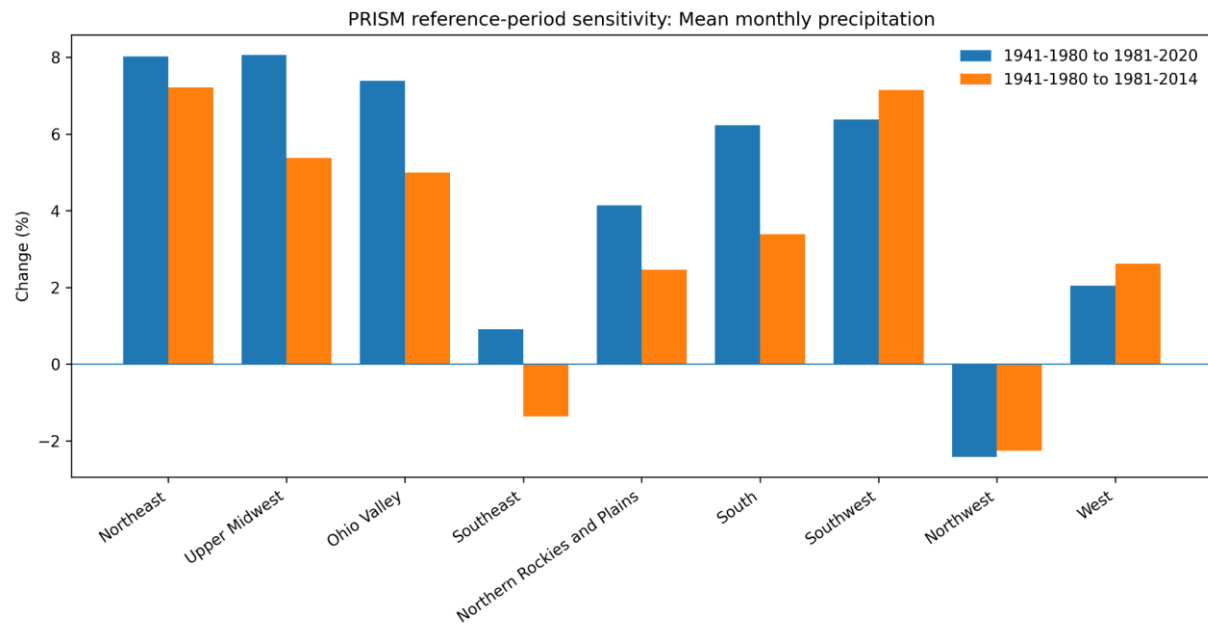


Figure S6a. PRISM reference-period sensitivity for mean monthly precipitation. The main observed comparison uses 1941-1980 to 1981-2020, while the sensitivity comparison uses 1941-1980 to 1981-2014.

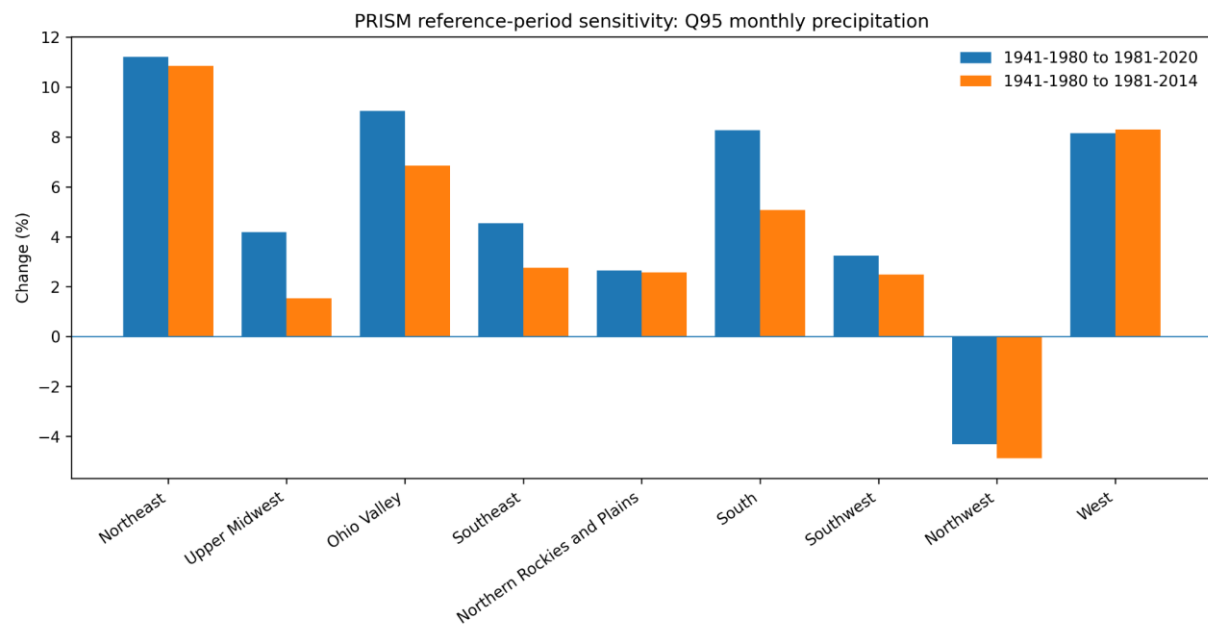


Figure S6b. PRISM reference-period sensitivity for Q95 monthly precipitation. The sensitivity test evaluates whether upper-tail change direction depends on ending the recent observed period in 2014 rather than 2020.

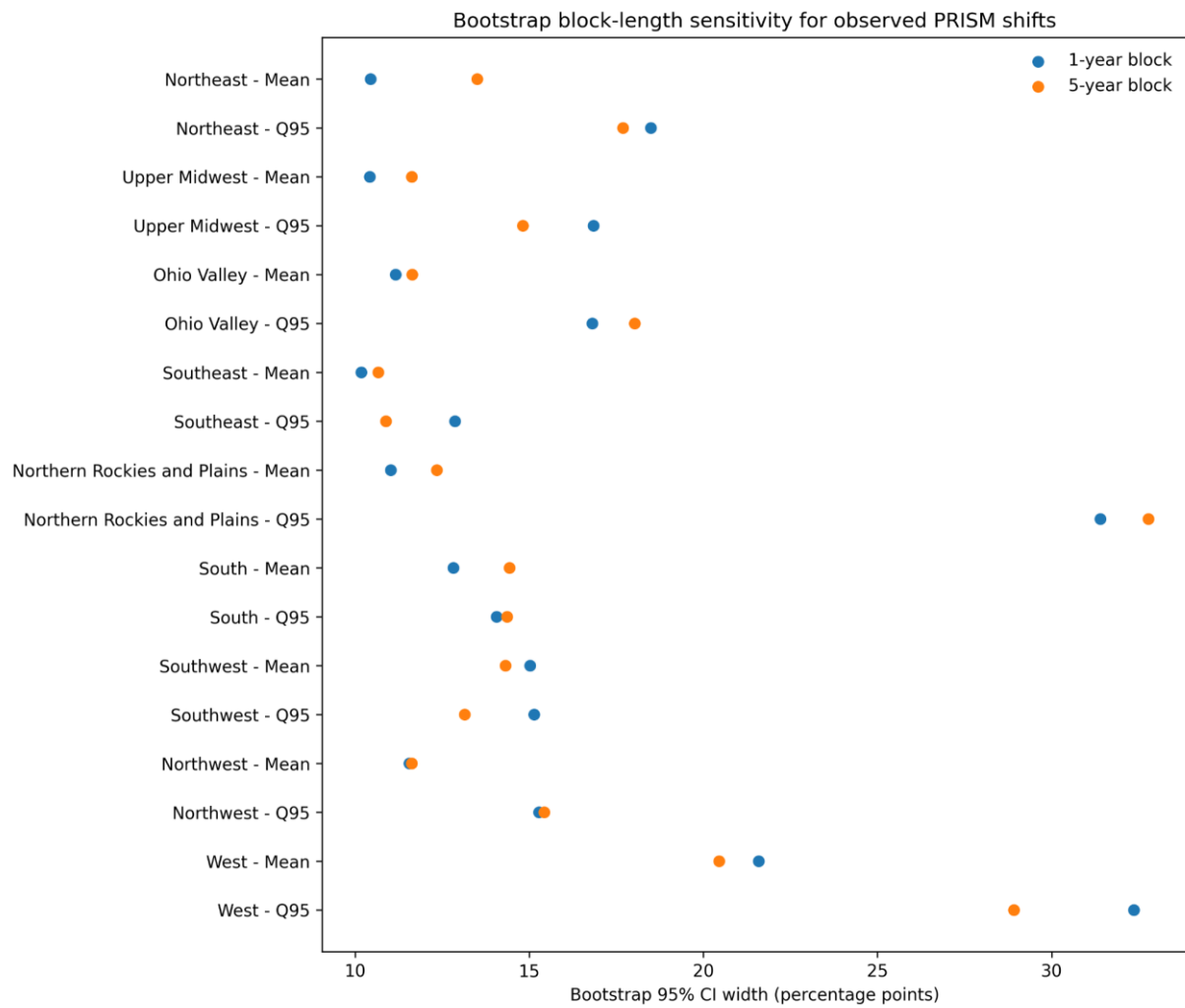


Figure S7. Bootstrap block-length sensitivity for observed PRISM shifts. Points compare the widths of 95% bootstrap confidence intervals obtained using 1-year and 5-year block resampling.

Additional CMIP6 leave-one-model-out sensitivity

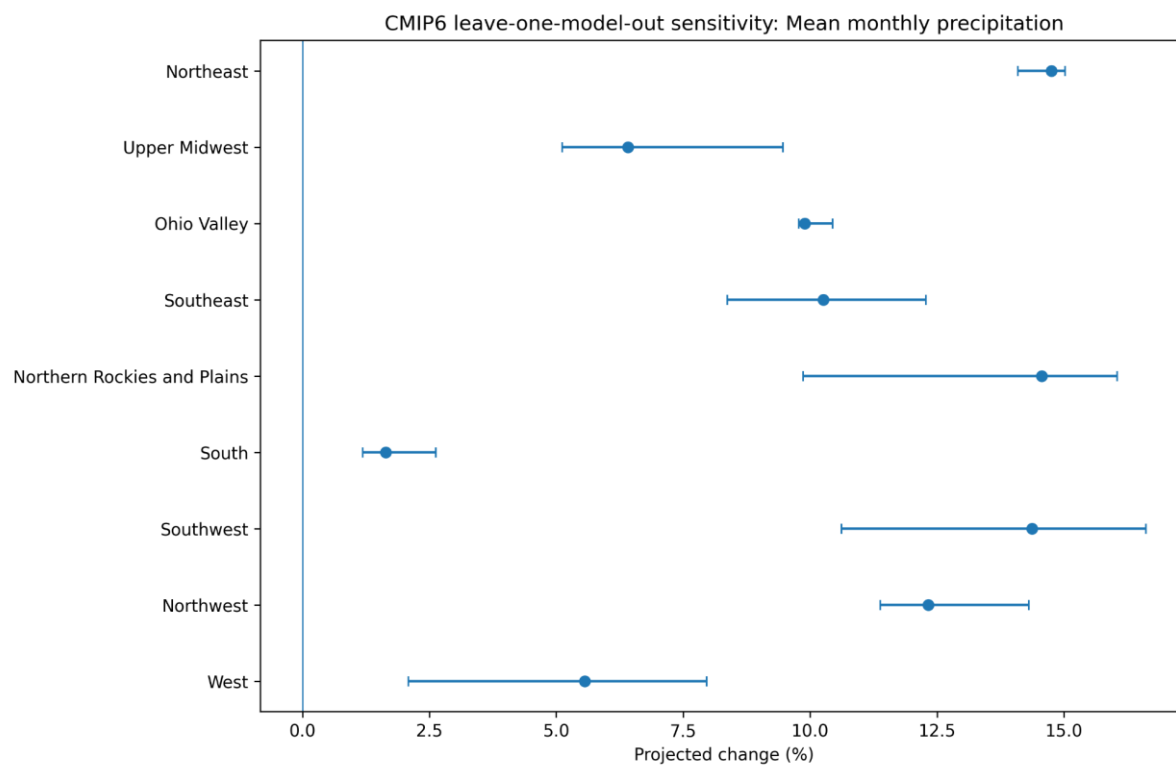


Figure S8a. CMIP6 leave-one-model-out sensitivity for SSP5-8.5 late-century mean monthly precipitation. Points show the five-model median, and horizontal ranges show the minimum and maximum medians obtained after omitting one selected model at a time.

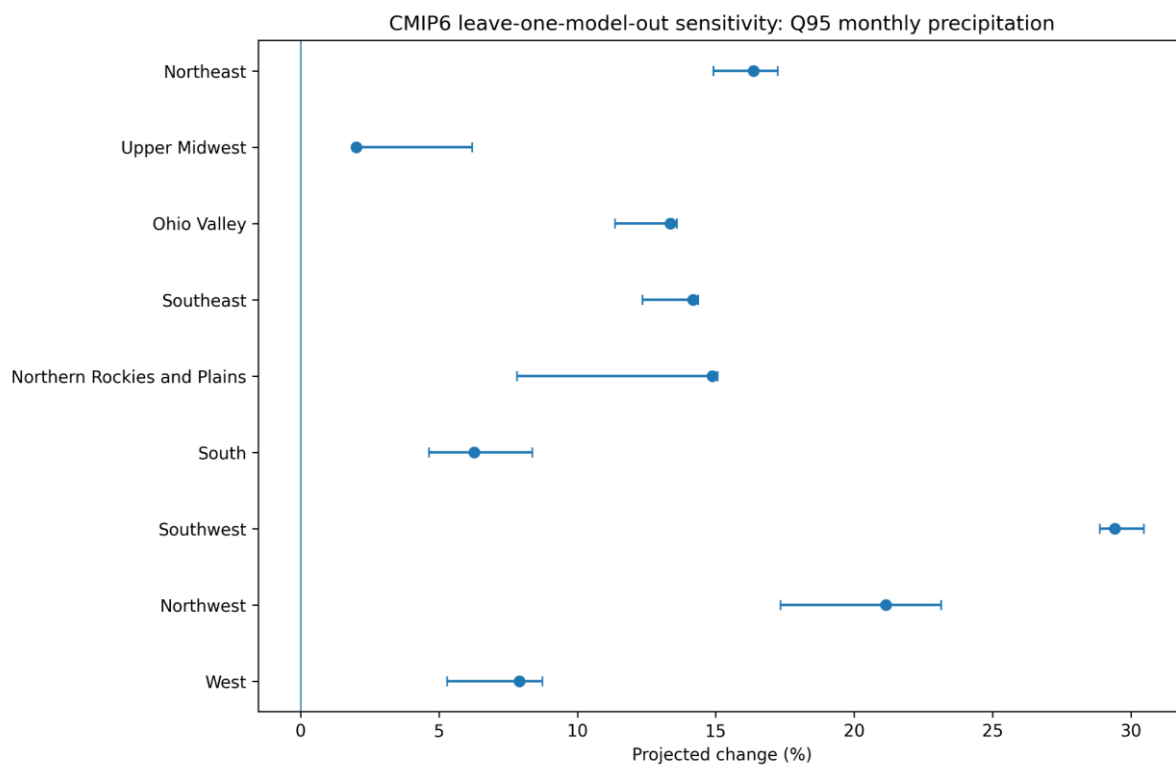


Figure S8b. CMIP6 leave-one-model-out sensitivity for SSP5-8.5 late-century Q95 monthly precipitation. The diagnostic evaluates whether selected-model medians are dominated by any single model and is descriptive rather than probabilistic.

Additional model-evaluation and screening diagnostics

This section provides supplementary figures and tables supporting the historical CMIP6 model evaluation, Taylor-diagram diagnostics, formal statistical testing, uncertainty/contextual diagnostics, and transparent screening-matrix rules.

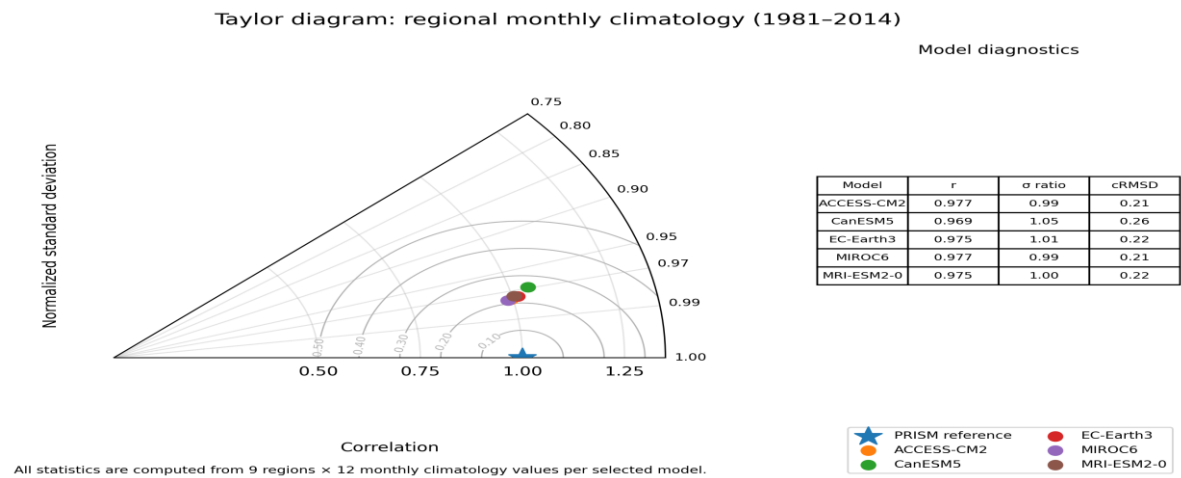


Figure S9. Taylor diagram for monthly climatology performance. The diagram summarizes the relative standard deviation, correlation, and centered RMSE of the selected CMIP6 model climatologies relative to PRISM.

PRISM versus selected CMIP6 historical monthly climatology (1981-2014)

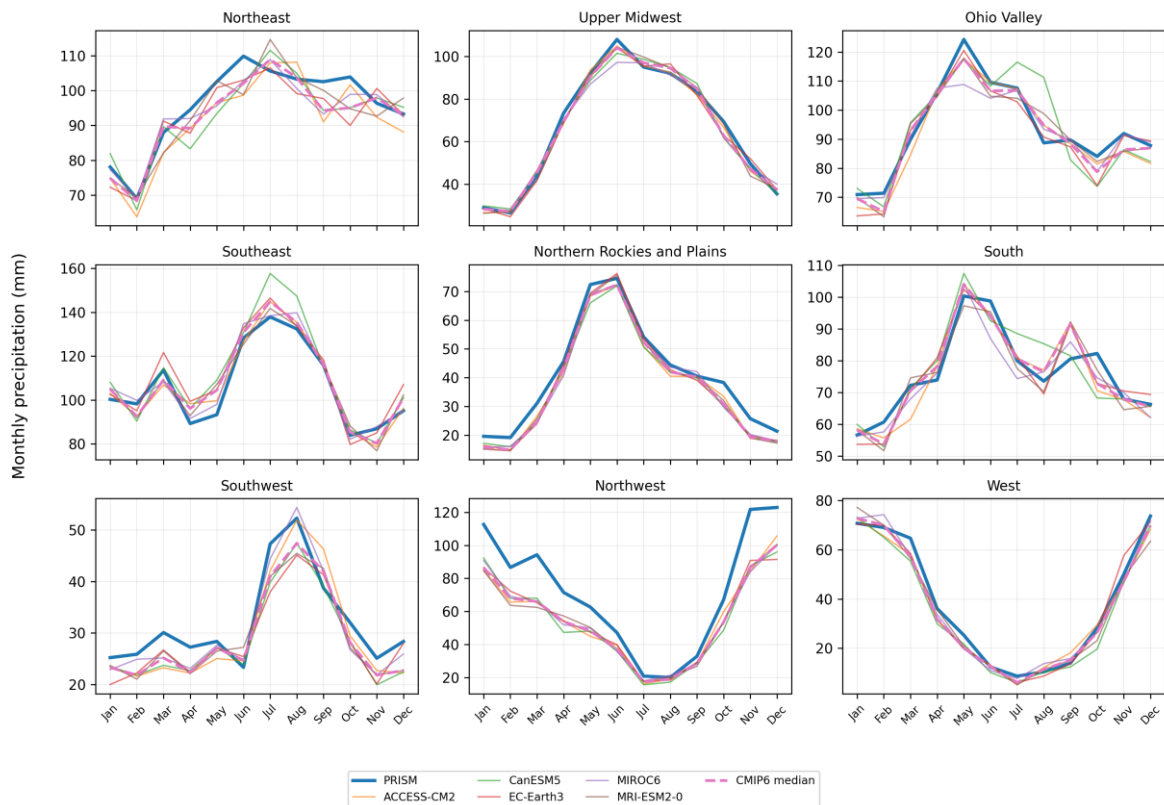


Figure S10. PRISM-CMIP6 12-month climatology validation panels. Panels compare the PRISM regional monthly climatological cycle with selected-model CMIP6 historical climatologies for 1981-2014.

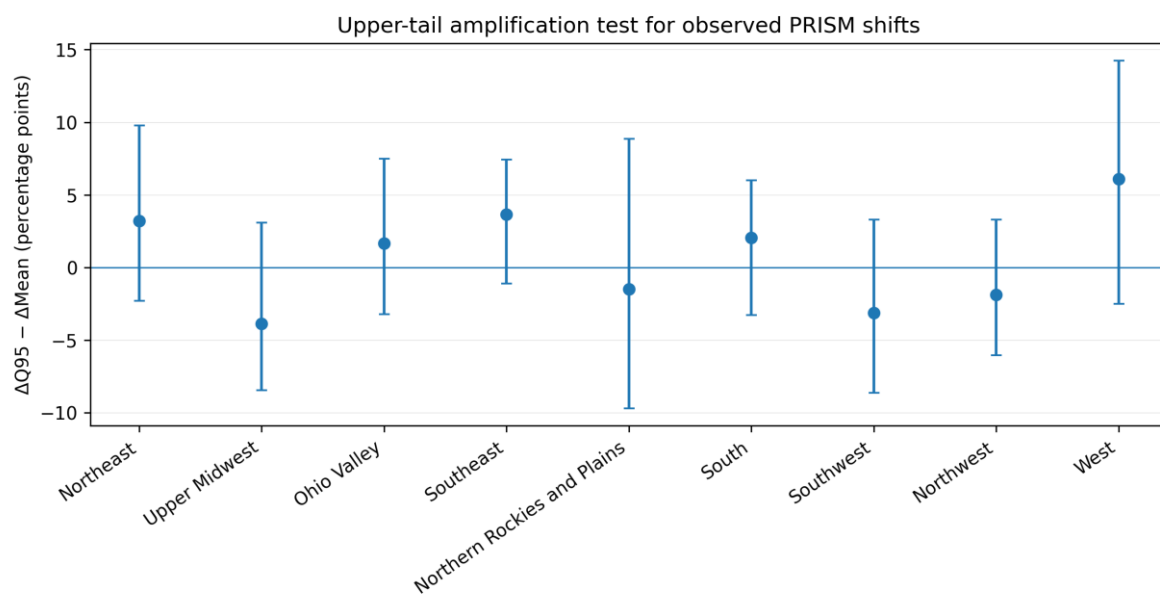


Figure S11. Upper-tail amplification tests. The figure summarizes region-wise bootstrap diagnostics for Delta Q95 minus Delta mean, with results interpreted under FDR-aware testing.

Observed temporal evolution of monthly precipitation indicators

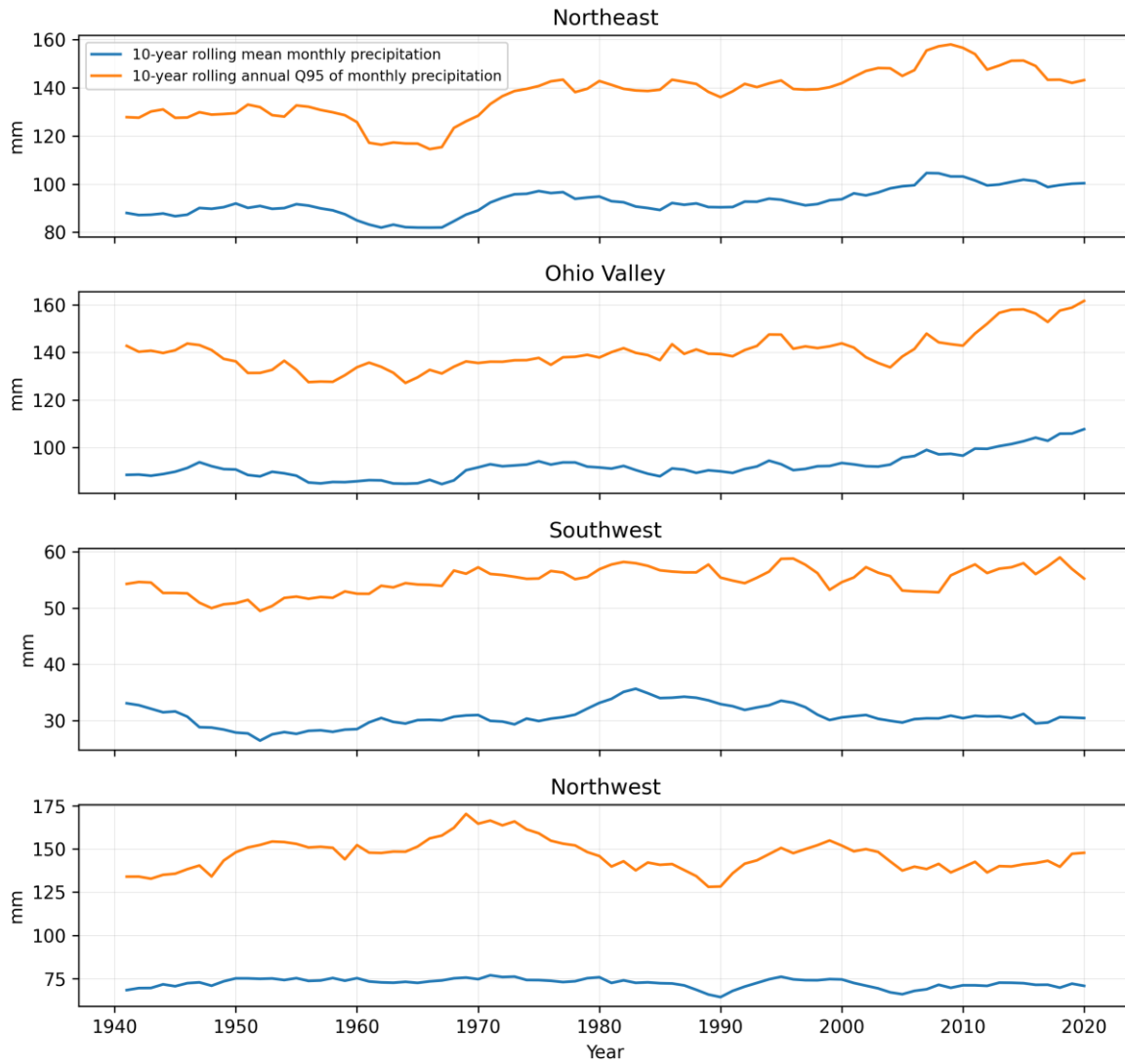


Figure S12. Temporal evolution diagnostics for observed indicators. Rolling observed diagnostics are provided as visual context for historical variability and should not be interpreted as formal trend attribution.

Supplementary Tables

Table S1. Data sources, temporal coverage, and role in the analysis.

Data source / framework	Variable or grouping	Temporal coverage	Use in analysis	Notes
PRISM monthly precipitation	Monthly precipitation total	1941-2020	Observed comparison: 1941-1980 vs 1981-2020	Aggregated to NOAA Climate Regions
NEX-GDDP-CMIP6	Daily precipitation (pr), converted to monthly totals	Historical 1981-2014; future 2021-2100	Reference: 1981-2014; future: 2021-2060 and 2061-2100	Model-specific changes, then ensemble summaries
CMIP6 scenarios	SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5	2021-2100	Two future periods	Five-model selected ensemble
Regional framework	NOAA Climate Regions	Contiguous United States	Common observed-projected spatial framework	Nine regions

Table S2. Full observed PRISM monthly distribution-shift metrics comparing 1941-1980 with 1981-2020.

Region	Mean (%)	Median (%)	CV (%)	Skewness change	Q95 (%)	Q99 (%)	Best fit early	Best fit recent
Northeast	8.0	4.5	7.6	0.0	11.2	11.1	Gamma	Gamma
Upper Midwest	8.1	17.7	-3.5	-0.0	4.2	8.3	Weibull	Weibull
Ohio Valley	7.4	3.1	-0.6	0.2	9.0	14.3	Weibull	Gamma
Southeast	0.9	0.7	0.8	0.1	4.6	-0.7	Weibull	Weibull
Northern Rockies and Plains	4.1	5.6	-1.0	-0.1	2.7	1.2	Lognormal	Lognormal
South	6.2	3.1	-0.5	0.4	8.3	11.8	Weibull	Gamma
Southwest	6.4	8.5	-4.1	-0.2	3.2	5.6	Gamma	Gamma
Northwest	-2.4	2.4	-0.9	-0.1	-4.3	-3.5	Weibull	Weibull
West	2.1	-2.0	8.4	0.2	8.1	17.3	Gamma	Gamma

Table S3. Observed seasonal mean precipitation shifts with percentile-based 95% bootstrap confidence intervals.

Region	Season	Change (%)	95% CI (%)	Bootstrap result
Northeast	DJF	2.7	[-5.7, 12.1]	Not robust
Northeast	MAM	6.2	[-2.2, 15.7]	Not robust
Northeast	JJA	10.5	[3.4, 18.0]	Robust
Northeast	SON	10.5	[1.4, 20.2]	Robust
Upper Midwest	DJF	9.2	[-2.7, 22.9]	Not robust
Upper Midwest	MAM	6.8	[-1.6, 15.9]	Not robust
Upper Midwest	JJA	3.9	[-2.6, 11.0]	Not robust
Upper Midwest	SON	15.6	[3.5, 29.9]	Robust
Ohio Valley	DJF	7.2	[-2.7, 19.0]	Not robust
Ohio Valley	MAM	6.4	[-2.6, 15.7]	Not robust
Ohio Valley	JJA	4.6	[-2.8, 12.1]	Not robust
Ohio Valley	SON	12.3	[2.1, 23.4]	Robust
Southeast	DJF	2.5	[-6.8, 12.8]	Not robust
Southeast	MAM	-7.6	[-15.9, 1.2]	Not robust
Southeast	JJA	1.7	[-5.3, 9.0]	Not robust
Southeast	SON	7.5	[-3.5, 19.5]	Not robust
Northern Rockies and Plains	DJF	-6.5	[-14.5, 2.5]	Not robust
Northern Rockies and Plains	MAM	8.3	[0.1, 17.4]	Robust
Northern Rockies and Plains	JJA	0.3	[-8.2, 9.6]	Not robust
Northern Rockies and Plains	SON	12.7	[-0.2, 27.9]	Not robust
South	DJF	9.9	[-1.1, 22.4]	Not robust
South	MAM	1.2	[-8.0, 11.8]	Not robust
South	JJA	7.0	[-1.9, 17.2]	Not robust
South	SON	8.7	[-3.7, 22.0]	Not robust
Southwest	DJF	7.6	[-7.3, 26.0]	Not robust
Southwest	MAM	4.3	[-9.0, 19.7]	Not robust
Southwest	JJA	3.3	[-4.6, 12.1]	Not robust
Southwest	SON	12.8	[-2.4, 30.7]	Not robust
Northwest	DJF	-8.0	[-17.3, 2.6]	Not robust
Northwest	MAM	8.9	[-0.4, 19.1]	Not robust
Northwest	JJA	-8.9	[-20.4, 5.0]	Not robust
Northwest	SON	-1.0	[-12.0, 11.2]	Not robust
West	DJF	3.7	[-13.2, 22.8]	Not robust
West	MAM	9.4	[-6.9, 29.5]	Not robust
West	JJA	-12.2	[-28.1, 7.8]	Not robust
West	SON	-2.5	[-19.0, 17.3]	Not robust

Table S4. CMIP6 ensemble monthly mean and Q95 precipitation shifts for all SSP scenarios and future periods.

Scenario	Period	Region	n models	Mean median (%)	Mean P10- P90 (%)	Q95 median (%)	Q95 P10- P90 (%)
SSP1-2.6	late_2061_2100	Northeast	5	8.4	[7.0, 11.9]	9.5	[6.3, 14.2]
SSP1-2.6	late_2061_2100	Upper Midwest	5	6.0	[2.4, 7.1]	3.9	[3.2, 7.3]
SSP1-2.6	late_2061_2100	Ohio Valley	5	4.1	[3.1, 6.6]	6.3	[1.9, 7.8]
SSP1-2.6	late_2061_2100	Southeast	5	4.1	[3.4, 10.8]	8.8	[6.0, 13.8]
SSP1-2.6	late_2061_2100	Northern Rockies and Plains	5	10.9	[4.8, 13.1]	13.3	[3.7, 17.0]
SSP1-2.6	late_2061_2100	South	5	2.1	[-1.3, 5.1]	0.6	[-1.9, 4.8]
SSP1-2.6	late_2061_2100	Southwest	5	5.9	[2.6, 13.9]	8.7	[2.7, 28.2]
SSP1-2.6	late_2061_2100	Northwest	5	7.0	[3.5, 11.4]	11.3	[8.0, 18.9]
SSP1-2.6	late_2061_2100	West	5	5.8	[-2.7, 8.9]	0.7	[-5.0, 16.7]
SSP1-2.6	near_mid_2021_2060	Northeast	5	6.9	[4.7, 9.6]	6.6	[0.6, 9.1]
SSP1-2.6	near_mid_2021_2060	Upper Midwest	5	4.1	[0.6, 8.2]	5.9	[-3.7, 9.1]
SSP1-2.6	near_mid_2021_2060	Ohio Valley	5	4.5	[1.3, 6.8]	4.9	[1.5, 7.8]
SSP1-2.6	near_mid_2021_2060	Southeast	5	4.3	[2.5, 8.7]	9.8	[6.7, 12.5]
SSP1-2.6	near_mid_2021_2060	Northern Rockies and Plains	5	6.6	[4.9, 10.4]	10.3	[1.9, 10.8]
SSP1-2.6	near_mid_2021_2060	South	5	0.1	[-2.2, 3.9]	1.3	[-4.9, 2.2]
SSP1-2.6	near_mid_2021_2060	Southwest	5	5.5	[3.4, 10.8]	12.5	[6.8, 16.3]
SSP1-2.6	near_mid_2021_2060	Northwest	5	6.5	[1.0, 7.6]	12.8	[5.1, 15.5]
SSP1-2.6	near_mid_2021_2060	West	5	-2.3	[-3.0, 10.5]	7.7	[3.9, 11.0]
SSP2-4.5	late_2061_2100	Northeast	5	11.4	[8.7, 13.1]	14.4	[8.9, 16.7]
SSP2-4.5	late_2061_2100	Upper Midwest	5	6.1	[4.5, 12.1]	4.5	[1.7, 11.6]
SSP2-4.5	late_2061_2100	Ohio Valley	5	5.9	[3.7, 7.9]	10.7	[3.7, 11.6]
SSP2-4.5	late_2061_2100	Southeast	5	5.7	[1.8, 14.5]	11.8	[4.5, 15.1]
SSP2-4.5	late_2061_2100	Northern Rockies and Plains	5	15.6	[3.9, 17.2]	15.2	[2.3, 16.4]
SSP2-4.5	late_2061_2100	South	5	1.0	[-2.6, 3.9]	3.4	[-2.3, 12.4]
SSP2-4.5	late_2061_2100	Southwest	5	4.6	[1.6, 5.6]	10.6	[4.2, 15.5]
SSP2-4.5	late_2061_2100	Northwest	5	10.5	[7.7, 13.4]	16.2	[8.8, 22.3]
SSP2-4.5	late_2061_2100	West	5	4.4	[-5.3, 16.5]	8.9	[-8.6, 20.9]
SSP2-4.5	near_mid_2021_2060	Northeast	5	7.5	[4.2, 8.1]	7.1	[5.2, 10.3]
SSP2-4.5	near_mid_2021_2060	Upper Midwest	5	2.6	[0.9, 8.7]	4.4	[-2.6, 11.1]
SSP2-4.5	near_mid_2021_2060	Ohio Valley	5	2.2	[1.3, 4.7]	5.9	[2.9, 9.0]
SSP2-4.5	near_mid_2021_2060	Southeast	5	3.3	[2.3, 10.2]	7.5	[4.7, 8.9]
SSP2-4.5	near_mid_2021_2060	Northern Rockies and Plains	5	5.5	[2.3, 11.9]	4.6	[0.5, 12.5]
SSP2-4.5	near_mid_2021_2060	South	5	1.9	[-3.9, 4.0]	0.2	[-3.5, 3.2]
SSP2-4.5	near_mid_2021_2060	Southwest	5	6.5	[2.9, 8.2]	6.5	[-0.9, 15.9]
SSP2-4.5	near_mid_2021_2060	Northwest	5	7.8	[2.5, 9.2]	10.6	[3.8, 19.0]
SSP2-4.5	near_mid_2021_2060	West	5	3.9	[1.6, 9.2]	7.7	[-0.8, 15.5]
SSP3-7.0	late_2061_2100	Northeast	5	13.2	[9.4, 13.4]	12.4	[7.3, 18.5]
SSP3-7.0	late_2061_2100	Upper Midwest	5	7.0	[2.8, 11.0]	5.8	[-2.8, 7.4]
SSP3-7.0	late_2061_2100	Ohio Valley	5	8.5	[8.1, 12.6]	12.8	[9.3, 18.6]
SSP3-7.0	late_2061_2100	Southeast	5	12.6	[4.7, 14.4]	11.8	[3.0, 14.3]
SSP3-7.0	late_2061_2100	Northern Rockies and Plains	5	13.6	[4.5, 19.3]	5.8	[2.2, 14.8]
SSP3-7.0	late_2061_2100	South	5	3.0	[0.4, 6.4]	2.0	[0.2, 9.1]
SSP3-7.0	late_2061_2100	Southwest	5	15.3	[4.6, 21.0]	32.3	[11.3, 41.0]
SSP3-7.0	late_2061_2100	Northwest	5	10.2	[7.1, 14.1]	17.4	[9.4, 18.9]
SSP3-7.0	late_2061_2100	West	5	3.2	[-0.4, 23.9]	14.5	[-1.1, 21.1]
SSP3-7.0	near_mid_2021_2060	Northeast	5	6.1	[3.5, 8.0]	6.1	[3.6, 8.9]
SSP3-7.0	near_mid_2021_2060	Upper Midwest	5	4.9	[1.4, 9.5]	5.3	[-3.0, 6.1]
SSP3-7.0	near_mid_2021_2060	Ohio Valley	5	5.0	[2.5, 6.1]	4.0	[3.5, 6.8]
SSP3-7.0	near_mid_2021_2060	Southeast	5	4.7	[2.5, 7.4]	7.0	[3.8, 10.8]
SSP3-7.0	near_mid_2021_2060	Northern Rockies and Plains	5	6.4	[5.0, 11.9]	7.0	[5.2, 13.1]
SSP3-7.0	near_mid_2021_2060	South	5	1.3	[-0.4, 3.2]	-2.7	[-3.5, 5.4]
SSP3-7.0	near_mid_2021_2060	Southwest	5	8.0	[-4.9, 10.5]	7.9	[-8.4, 19.6]
SSP3-7.0	near_mid_2021_2060	Northwest	5	4.9	[2.4, 7.2]	6.8	[5.4, 18.4]
SSP3-7.0	near_mid_2021_2060	West	5	-4.3	[-5.1, 10.0]	8.9	[-1.0, 10.7]
SSP5-8.5	late_2061_2100	Northeast	5	14.8	[10.8, 15.8]	16.4	[12.0, 21.9]
SSP5-8.5	late_2061_2100	Upper Midwest	5	6.4	[3.2, 14.0]	2.0	[-0.7, 12.0]
SSP5-8.5	late_2061_2100	Ohio Valley	5	9.9	[8.0, 12.6]	13.4	[8.3, 20.3]
SSP5-8.5	late_2061_2100	Southeast	5	10.3	[6.0, 14.9]	14.2	[9.6, 16.0]
SSP5-8.5	late_2061_2100	Northern Rockies and Plains	5	14.6	[2.5, 20.5]	14.9	[-2.0, 16.1]
SSP5-8.5	late_2061_2100	South	5	1.6	[-0.8, 5.4]	6.3	[0.2, 13.7]
SSP5-8.5	late_2061_2100	Southwest	5	14.4	[6.7, 22.5]	29.4	[26.0, 37.2]
SSP5-8.5	late_2061_2100	Northwest	5	12.3	[8.8, 17.0]	21.1	[11.7, 30.2]
SSP5-8.5	late_2061_2100	West	5	5.6	[-3.1, 17.2]	7.9	[-1.4, 24.6]
SSP5-8.5	near_mid_2021_2060	Northeast	5	8.6	[8.1, 9.3]	6.8	[4.8, 8.8]
SSP5-8.5	near_mid_2021_2060	Upper Midwest	5	4.9	[1.2, 8.3]	5.6	[-3.3, 7.9]
SSP5-8.5	near_mid_2021_2060	Ohio Valley	5	4.3	[2.5, 6.2]	6.6	[0.4, 9.6]
SSP5-8.5	near_mid_2021_2060	Southeast	5	3.0	[2.4, 9.6]	8.1	[5.7, 9.5]
SSP5-8.5	near_mid_2021_2060	Northern Rockies and Plains	5	9.7	[3.6, 11.8]	10.5	[2.1, 14.5]
SSP5-8.5	near_mid_2021_2060	South	5	1.1	[-3.2, 3.4]	2.4	[-3.0, 3.8]
SSP5-8.5	near_mid_2021_2060	Southwest	5	6.5	[-0.7, 10.2]	7.5	[4.4, 20.5]
SSP5-8.5	near_mid_2021_2060	Northwest	5	6.2	[4.8, 11.2]	10.9	[9.2, 17.1]
SSP5-8.5	near_mid_2021_2060	West	5	2.6	[-3.8, 6.3]	6.2	[-3.1, 13.1]

Table S5. CMIP6 ensemble seasonal mean precipitation shifts under SSP5-8.5 during 2061-2100.

Region	Season	n models	Mean median (%)	Mean P10-P90 (%)	Mean min-max (%)
Northeast	DJF	5	34.2	[22.6, 41.9]	[22.6, 43.6]
Northeast	JJA	5	6.4	[3.9, 7.9]	[2.5, 8.1]
Northeast	MAM	5	15.8	[11.7, 26.6]	[9.3, 32.7]
Northeast	SON	5	4.7	[-5.8, 7.2]	[-9.4, 8.0]
Upper Midwest	DJF	5	37.1	[23.8, 38.1]	[22.0, 38.2]
Upper Midwest	JJA	5	-8.6	[-16.7, 0.0]	[-20.5, 5.3]
Upper Midwest	MAM	5	20.1	[9.6, 36.3]	[6.0, 46.3]
Upper Midwest	SON	5	8.3	[2.2, 12.4]	[0.4, 13.9]
Ohio Valley	DJF	5	22.3	[16.0, 31.3]	[15.6, 36.0]
Ohio Valley	JJA	5	5.9	[-7.2, 15.1]	[-11.6, 18.1]
Ohio Valley	MAM	5	12.6	[9.6, 16.6]	[8.1, 18.8]
Ohio Valley	SON	5	1.5	[-5.4, 8.6]	[-8.7, 11.0]
Southeast	DJF	5	9.2	[3.2, 23.5]	[-0.3, 26.5]
Southeast	JJA	5	14.4	[1.9, 22.4]	[0.5, 25.9]
Southeast	MAM	5	6.0	[-2.1, 12.4]	[-6.3, 14.3]
Southeast	SON	5	10.2	[1.3, 20.1]	[-2.3, 22.5]
Northern Rockies and Plains	DJF	5	36.0	[30.8, 40.2]	[29.5, 41.7]
Northern Rockies and Plains	JJA	5	-4.7	[-16.2, 16.6]	[-19.0, 17.2]
Northern Rockies and Plains	MAM	5	19.9	[17.0, 32.6]	[15.9, 36.7]
Northern Rockies and Plains	SON	5	6.7	[-1.7, 12.8]	[-3.4, 16.5]
South	DJF	5	-1.0	[-6.3, 11.5]	[-8.5, 13.3]
South	JJA	5	9.6	[-9.8, 18.8]	[-13.0, 23.3]
South	MAM	5	1.8	[-11.2, 6.3]	[-16.3, 8.3]
South	SON	5	4.7	[-4.6, 8.1]	[-5.4, 8.6]
Southwest	DJF	5	0.8	[-4.8, 24.6]	[-6.1, 25.4]
Southwest	JJA	5	28.2	[21.9, 44.5]	[20.8, 44.5]
Southwest	MAM	5	-10.2	[-18.2, 6.8]	[-18.6, 8.5]
Southwest	SON	5	13.3	[8.6, 15.2]	[6.9, 15.6]
Northwest	DJF	5	20.6	[10.7, 23.0]	[10.2, 23.9]
Northwest	JJA	5	-12.1	[-20.7, 18.6]	[-23.2, 22.4]
Northwest	MAM	5	14.0	[6.2, 23.0]	[6.2, 25.5]
Northwest	SON	5	15.5	[2.9, 19.7]	[-1.9, 21.7]
West	DJF	5	5.1	[-5.9, 27.0]	[-11.7, 33.9]
West	JJA	5	38.2	[12.3, 114.7]	[3.7, 141.7]
West	MAM	5	-11.0	[-13.3, -1.6]	[-13.7, 1.0]
West	SON	5	0.3	[-13.1, 21.3]	[-17.5, 26.5]

Table S6. Selected-model spread in SSP5-8.5 late-century monthly mean and Q95 precipitation shifts. Min-max values describe the full range among the selected five models.

Region	n model s	Mean median (%)	Mean P10-P90 (%)	Mean min-max (%)	Q95 median (%)	Q95 P10-P90 (%)	Q95 min-max (%)
Northeast	5	14.8	[10.8, 15.8]	[9.0, 16.1]	16.4	[12.0, 21.9]	[11.1, 24.4]
Upper Midwest	5	6.4	[3.2, 14.0]	[2.8, 15.0]	2.0	[-0.7, 12.0]	[-2.4, 13.1]
Ohio Valley	5	9.9	[8.0, 12.6]	[6.9, 13.7]	13.4	[8.3, 20.3]	[7.5, 24.6]
Southeast	5	10.3	[6.0, 14.9]	[5.8, 15.3]	14.2	[9.6, 16.0]	[9.0, 17.0]
Northern Rockies and Plains	5	14.6	[2.5, 20.5]	[0.7, 22.5]	14.9	[-2.0, 16.1]	[-3.8, 16.7]
South	5	1.6	[-0.8, 5.4]	[-1.9, 6.6]	6.3	[0.2, 13.7]	[-1.6, 15.9]
Southwest	5	14.4	[6.7, 22.5]	[6.7, 24.9]	29.4	[26.0, 37.2]	[24.4, 41.0]
Northwest	5	12.3	[8.8, 17.0]	[7.6, 17.5]	21.1	[11.7, 30.2]	[10.4, 33.6]
West	5	5.6	[-3.1, 17.2]	[-4.2, 21.8]	7.9	[-1.4, 24.6]	[-4.1, 34.7]

Table S7. PRISM reference-period sensitivity analysis. Main values compare 1941-1980 with 1981-2020; sensitivity values compare 1941-1980 with 1981-2014. Full confidence intervals are supplied in the accompanying CSV file.

Region	Mean main %	Mean sens. %	Mean direction	Q95 main %	Q95 sens. %	Q95 direction
Northeast	8.02	7.21	same	11.21	10.85	same
Upper Midwest	8.06	5.37	same	4.19	1.53	same
Ohio Valley	7.39	4.99	same	9.04	6.85	same
Southeast	0.91	-1.36	different	4.55	2.75	same
Northern Rockies and Plains	4.14	2.46	same	2.65	2.58	same
South	6.23	3.39	same	8.27	5.07	same
Southwest	6.38	7.14	same	3.25	2.49	same
Northwest	-2.42	-2.25	same	-4.31	-4.88	same
West	2.05	2.62	same	8.14	8.29	same

Table S8. Bootstrap block-length sensitivity analysis. The point estimate is the same for both bootstrap designs; confidence intervals and robust/not-robust classifications are compared between 1-year and 5-year block resampling. The final column reports classification-change direction and identifies boundary-sensitive cases when relevant.

In this table, classification changes occur in both directions: Ohio Valley Q95 changes from robust to not robust, whereas Southwest mean and Southwest Q95 change from not robust to robust under the 5-year block design. South mean remains not robust under both the primary and 5-year block classifications, but it is marked as boundary-sensitive because its primary interval touches zero.

Region	Metric	Change %	1-year CI %	1-year result	5-year CI %	5-year result	Change direction
Northeast	Mean	8.02	[2.88, 13.33]	Robust	[0.86, 14.37]	Robust	No change
Northeast	Q95	11.21	[3.17, 21.66]	Robust	[2.64, 20.33]	Robust	No change
Upper Midwest	Mean	8.06	[2.94, 13.36]	Robust	[2.31, 13.94]	Robust	No change
Upper Midwest	Q95	4.19	[-2.68, 14.16]	Not robust	[-1.60, 13.22]	Not robust	No change
Ohio Valley	Mean	7.39	[1.92, 13.08]	Robust	[0.77, 12.41]	Robust	No change
Ohio Valley	Q95	9.04	[1.21, 18.02]	Robust	[-2.06, 15.97]	Not robust	Robust to not robust
Southeast	Mean	0.91	[-4.14, 6.04]	Not robust	[-5.33, 5.34]	Not robust	No change
Southeast	Q95	4.55	[-3.06, 9.81]	Not robust	[-2.25, 8.63]	Not robust	No change
Northern Rockies and Plains	Mean	4.14	[-1.23, 9.79]	Not robust	[-2.29, 10.06]	Not robust	No change
Northern Rockies and Plains	Q95	2.65	[-11.29, 20.11]	Not robust	[-11.83, 20.94]	Not robust	No change
South	Mean	6.23	[0.00, 12.98]	Not robust	[-0.46, 13.97]	Not robust	No change; boundary-sensitive
South	Q95	8.27	[0.32, 14.38]	Robust	[0.81, 15.17]	Robust	No change
Southwest	Mean	6.38	[-1.04, 13.98]	Not robust	[1.58, 15.90]	Robust	Not robust to robust
Southwest	Q95	3.25	[-3.32, 11.82]	Not robust	[0.92, 14.06]	Robust	Not robust to robust
Northwest	Mean	-2.42	[-7.88, 3.68]	Not robust	[-9.06, 2.57]	Not robust	No change
Northwest	Q95	-4.31	[-11.82, 3.46]	Not robust	[-12.36, 3.07]	Not robust	No change
West	Mean	2.05	[-8.26, 13.33]	Not robust	[-7.07, 13.38]	Not robust	No change
West	Q95	8.14	[-7.35, 25.01]	Not robust	[-2.48, 26.43]	Not robust	No change

Table S9. Selected NEX-GDDP-CMIP6 model coverage and rationale. All listed models provided complete precipitation coverage for the historical experiment and the four SSP scenarios used in the study.

Model	Modeling center / institution	Historical	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5	Selection rationale
ACCESS-CM2	CSIRO-ARCCSS, Australia	Available	Available	Available	Available	Available	Complete NEX-GDDP-CMIP6 precipitation coverage for all experiments used here
CanESM5	Canadian Centre for Climate Modelling and Analysis, Canada	Available	Available	Available	Available	Available	Complete NEX-GDDP-CMIP6 precipitation coverage for all experiments used here
EC-Earth3	EC-Earth Consortium	Available	Available	Available	Available	Available	Complete NEX-GDDP-CMIP6 precipitation coverage for all experiments used here
MRI-ESM2-0	Meteorological Research Institute, Japan	Available	Available	Available	Available	Available	Complete NEX-GDDP-CMIP6 precipitation coverage for all experiments used here
MIROC6	MIROC consortium, Japan	Available	Available	Available	Available	Available	Complete NEX-GDDP-CMIP6 precipitation coverage for all experiments used here

Table S10. CMIP6 leave-one-model-out sensitivity for SSP5-8.5 late-century monthly mean and Q95 precipitation. The five-model median is compared with the range of medians obtained after omitting one model at a time.

Region	Metric	Five-model median (%)	LOO min (%)	LOO max (%)	Max LOO shift (pp)	Interpretation
Northeast	Mean	14.8	14.1	15.0	0.7	Very stable (<1 pp)
Northeast	Q95	16.4	14.9	17.2	1.4	Stable (<3 pp)
Upper Midwest	Mean	6.4	5.1	9.5	3.0	Moderate sensitivity (3-5 pp)
Upper Midwest	Q95	2.0	1.9	6.2	4.2	Moderate sensitivity (3-5 pp)
Ohio Valley	Mean	9.9	9.8	10.4	0.5	Very stable (<1 pp)
Ohio Valley	Q95	13.4	11.4	13.6	2.0	Stable (<3 pp)
Southeast	Mean	10.3	8.4	12.3	2.0	Stable (<3 pp)
Southeast	Q95	14.2	12.4	14.4	1.8	Stable (<3 pp)
Northern Rockies and Plains	Mean	14.6	9.9	16.1	4.7	Moderate sensitivity (3-5 pp)
Northern Rockies and Plains	Q95	14.9	7.8	15.1	7.1	High sensitivity (>=5 pp)
South	Mean	1.6	1.2	2.6	1.0	Very stable (<1 pp)
South	Q95	6.3	4.6	8.4	2.1	Stable (<3 pp)
Southwest	Mean	14.4	10.6	16.6	3.8	Moderate sensitivity (3-5 pp)
Southwest	Q95	29.4	28.9	30.5	1.0	Stable (<3 pp)
Northwest	Mean	12.3	11.4	14.3	2.0	Stable (<3 pp)
Northwest	Q95	21.1	17.3	23.1	3.8	Moderate sensitivity (3-5 pp)
West	Mean	5.6	2.1	8.0	3.5	Moderate sensitivity (3-5 pp)
West	Q95	7.9	5.3	8.7	2.6	Stable (<3 pp)

Table S11. Historical CMIP6 model-evaluation metrics. A compact version is shown below; the complete table is also provided as CSV in the supplementary archive.

model	region	percent_ bias	rmse_ mm	nrmse_p ercent	pearson_ r	kge	monthly_cli matology_r	monthly_climat ology_kge
ACCESS-CM2	Northeast	-4.58	41.2	43.2	0.182	0.169	0.934	0.887
ACCESS-CM2	Northern Rockies and Plains	-9.44	18.8	46.4	0.669	0.642	0.997	0.901
ACCESS-CM2	Northwest	-22.3	44.1	61.5	0.532	0.433	0.979	0.663
ACCESS-CM2	Ohio Valley	-2.87	40	42.8	0.243	0.234	0.973	0.922
ACCESS-CM2	South	-1.15	38.4	50.5	0.206	0.206	0.903	0.823
ACCESS-CM2	Southeast	0.725	46.3	43.6	0.276	0.274	0.962	0.916
ACCESS-CM2	Southwest	-7.61	21.1	66.1	0.302	0.269	0.934	0.81
ACCESS-CM2	Upper Midwest	-1.32	31.2	47	0.601	0.6	0.996	0.983
ACCESS-CM2	West	-4.81	37.1	96.3	0.483	0.471	0.991	0.927
CanESM5	Northeast	-2.78	41.7	43.7	0.126	0.108	0.873	0.87
CanESM5	Northern Rockies and Plains	-10	18.8	46.2	0.684	0.663	0.993	0.899
CanESM5	Northwest	-24	44.3	61.7	0.539	0.43	0.99	0.659
CanESM5	Ohio Valley	-0.195	42.4	45.4	0.222	0.222	0.865	0.799
CanESM5	South	0.9	39.2	51.5	0.224	0.221	0.876	0.81
CanESM5	Southeast	4.84	47.9	45	0.276	0.275	0.946	0.721
CanESM5	Southwest	-11.4	21.9	68.4	0.196	0.178	0.96	0.869
CanESM5	Upper Midwest	-1.13	29	43.6	0.651	0.648	0.991	0.975
CanESM5	West	-9.21	40.9	106	0.38	0.367	0.992	0.907
EC-Earth3	Northeast	-3.18	42.3	44.3	0.149	0.14	0.911	0.902
EC-Earth3	Northern Rockies and Plains	-7.6	19.6	48.2	0.666	0.658	0.994	0.88
EC-Earth3	Northwest	-22.5	43.2	60.3	0.548	0.434	0.994	0.637
EC-Earth3	Ohio Valley	-2.97	40.9	43.7	0.263	0.262	0.973	0.905
EC-Earth3	South	-0.295	38.4	50.4	0.199	0.199	0.921	0.86
EC-Earth3	Southeast	4.01	48.7	45.9	0.194	0.189	0.962	0.895
EC-Earth3	Southwest	-10.3	20.1	62.9	0.256	0.248	0.925	0.836
EC-Earth3	Upper Midwest	-1.67	30.9	46.4	0.612	0.611	0.994	0.981
EC-Earth3	West	-3.46	39.4	102	0.457	0.455	0.991	0.959
MIROC6	Northeast	-2.23	41.1	43	0.183	0.171	0.935	0.879
MIROC6	Northern Rockies and Plains	-8.65	18.6	45.8	0.683	0.664	0.991	0.902
MIROC6	Northwest	-22.3	40.2	56.1	0.626	0.499	0.986	0.654
MIROC6	Ohio Valley	-1.91	43.1	46.1	0.134	0.129	0.948	0.86
MIROC6	South	-2.26	40.6	53.3	0.165	0.162	0.925	0.921
MIROC6	Southeast	1.64	46.8	44	0.285	0.285	0.984	0.931
MIROC6	Southwest	-5.27	22.3	69.6	0.292	0.23	0.969	0.854
MIROC6	Upper Midwest	-2.25	30.8	46.2	0.592	0.583	0.99	0.921
MIROC6	West	-2.56	39.8	103	0.437	0.435	0.99	0.972
MRI-ESM2-0	Northeast	-2.08	40.4	42.3	0.195	0.18	0.903	0.886
MRI-ESM2-0	Northern Rockies and Plains	-8.35	20.2	49.9	0.636	0.626	0.996	0.882
MRI-ESM2-0	Northwest	-23.1	41.3	57.6	0.601	0.464	0.987	0.639
MRI-ESM2-0	Ohio Valley	-1.65	42.4	45.3	0.171	0.166	0.947	0.943
MRI-ESM2-0	South	-1.36	39.8	52.3	0.2	0.197	0.933	0.902
MRI-ESM2-0	Southeast	1.23	48	45.2	0.242	0.241	0.942	0.935
MRI-ESM2-0	Southwest	-9.42	19.7	61.7	0.319	0.307	0.923	0.866
MRI-ESM2-0	Upper Midwest	-0.899	32	48.1	0.579	0.577	0.994	0.972
MRI-ESM2-0	West	-5.08	39.1	101	0.437	0.429	0.984	0.946

Table S12. Hypothesis-testing, FDR, and effect-size results. A compact version is shown below; the full 26-column table is provided as CSV in the supplementary archive.

Hypothesis	Primary test	Metric/family	Main result	Interpretation
H1	omnibus regional heterogeneity permutation	mean	p=0.294	regional heterogeneity not supported at 0.05
H1	omnibus regional heterogeneity permutation	Q95	p=0.189	regional heterogeneity not supported at 0.05
H2	bootstrap Delta Q95 minus Delta mean with BH-FDR	region-wise amplification tests	0/9 regions FDR-significant	upper-tail amplification not formally supported
H3	comparison with PRISM bootstrapped 40-year historical-change envelope	SSP5-8.5 late mean and Q95, region-wise	14/18 region-metric pairs outside envelope	screening diagnostic, not attribution or validation
H4	permutation test of between-model performance differences	KGE, nRMSE, climatology correlation	0/3 model-performance tests FDR-significant	descriptive model ranking remains informative

Table S13. Bootstrap parameter justification and sensitivity summary.

Item	Value	Justification
Bootstrap replicates	5000	Used to stabilize percentile confidence intervals for observed PRISM shifts.
Primary block design	1-year year-block resampling	Preserves the 12-month structure within each resampled year.
Sensitivity block design	5-year block resampling	Evaluates sensitivity of robustness labels to multi-year precipitation variability.
Confidence interval	Percentile-based 95% interval	Does not require symmetric bootstrap distributions.
Robust/not robust rule	CI excludes zero = robust; CI includes or touches zero = not robust	Provides a conservative interpretation of boundary cases.
FDR handling	Benjamini-Hochberg applied within predefined families	Avoids mixing unrelated hypothesis families.

Table S14a. Screening-matrix if-then decision rules and priority order.

Priority order	Category / qualifier	Rule type	If-then rule	Interpretation
1	E	primary category	If observed and projected mean or Q95 directions diverge, assign E unless a stronger aligned or emerging signal is reported as the main precipitation-screening result.	Directional uncertainty; avoid assuming continuation of observed historical direction.
2	A	primary category	If observed mean or Q95 signal is positive and robust and projected mean or Q95 is positive, assign A.	Observed and projected precipitation diagnostics point in an aligned positive direction.
3	B	primary category	If observed signal is weak or not robust but projected Q95 increase is strong relative to other regions, assign B.	Future high-month precipitation deserves follow-up even if historical signal is weak.
4	C	primary category	If seasonal redistribution is the dominant projected diagnostic, assign C.	Seasonal timing may affect storage, snow-rain partition, recharge, or runoff timing.
5	U	primary category	If no primary rule provides a strong screening signal, assign U.	No strong screening priority based on current diagnostics.
6	Confidence qualifier	qualifier only	Historical model skill and selected-model spread are reported as confidence qualifiers and do not override the primary hydroclimatic category.	Model skill/spread limits confidence in magnitude and should be interpreted separately.

Table S14b. Regional assignments from the categorical Hydroclimatic Screening Matrix.

region	primary_category	primary_interpretation	observed_basis	projected_basis	confidence_qualifier
Northeast	A	Aligned planning-relevant precipitation signal	mean 8.0%, Q95 11.2%	mean 14.8%, Q95 16.4%	reported separately
Upper Midwest	A	Aligned planning-relevant precipitation signal	mean 8.1%, Q95 4.2%	mean 6.4%, Q95 2.0%	reported separately
Ohio Valley	A	Aligned planning-relevant precipitation signal	mean 7.4%, Q95 9.0%	mean 9.9%, Q95 13.4%	reported separately
Southeast	U	Unclassified / weak screening signal	mean 0.9%, Q95 4.6%	mean 10.3%, Q95 14.2%	reported separately
Northern Rockies and Plains	B	Emerging upper-tail concern	mean 4.1%, Q95 2.7%	mean 14.6%, Q95 14.9%	reported separately
South	A	Aligned planning-relevant precipitation signal	mean 6.2%, Q95 8.3%	mean 1.6%, Q95 6.3%	reported separately
Southwest	B	Emerging upper-tail concern	mean 6.4%, Q95 3.2%	mean 14.4%, Q95 29.4%	reported separately
Northwest	E	Directional uncertainty; avoid trend-continuation assumptions	mean -2.4%, Q95 -4.3%	mean 12.3%, Q95 21.1%	reported separately
West	C	Seasonal-storage follow-up priority	mean 2.1%, Q95 8.1%	mean 5.6%, Q95 7.9%	reported separately