Electronic Supplementary Material to: Characterization and Propagation of Historical and Projected Droughts in the Umatilla River Basin, Oregon, USA*

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Table S1. Climate models used to obtain projected climate data in the Umatilla River Basin (URB)

S. N.	Model	Center	Atm. Res. (Long × Lat)
1	BCC-CSM1-1	Beijing Climate Center, China Meteorological Administration	2.8 × 2.8
2	CanESM2	Canadian Centre for Climate Modeling and Analysis	2.8 × 2.8
3	CCSM4	National Center of Atmospheric Research, USA	1.25 × 0.94
4	GFDL-ESM2G	NOAA Geophysical Fluid Dynamics Laboratory	2.5 × 2.0
5	GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory	2.5 × 2.0
6	inmcm4	Institute for Numerical Mathematics, Russia	2.0 × 1.5
7	IPSL-CM5A-LR	Institut Pierre Simon Laplace, France	3.75 × 1.8
8	IPSL-CM5A-MR	Institut Pierre Simon Laplace, France	2.5 × 1.25
9	IPSL-CM5B-LR	Institut Pierre Simon Laplace, France	3.75 × 1.8
10	MIROC5	Atmosphere and Ocean Research Institute, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	1.4 × 1.4

Results

Maximum drought duration

The maximum drought duration in the URB (Fig. S4) showed similar behavior to the average drought duration. The maximum drought duration for meteorological drought was found to have a shorter duration (average of 14.5 months) compared to the hydrological (25 months) and agricultural droughts (30 months) of the historical period. This suggests that a 3-month (seasonal) period of anomalies in precipitation, evapotranspiration, and soil moisture can lead to extreme droughts that persist from 14.5 to 30 months during the historical period. The SPI-based maximum drought duration in future scenarios is projected to increase by up to 14%, whereas the SPEI-based maximum drought duration is projected to increase by up to 30% over the historical period.

Maximum hydrological drought duration was found to be higher in future scenarios compared to the historical period by an average of 14%. Projected maximum drought durations in future scenarios increased by more than 20% in Zone 2 during all future scenarios except for RCP 8.5 mid-century. Maximum agricultural drought duration increased in all the zones during RCP 8.5 late-century and in Zones 3 and 4 during RCP 4.5 late-century.

Maximum drought severity

The maximum drought severity in the URB (Fig. S5) showed similar behavior to the average drought severity. The maximum drought severity for meteorological drought was found to be smaller (average of 16) compared to the hydrological (average of 26) and agricultural droughts (average of 37) for the historical period. SPI-based maximum drought severity in the future scenarios is projected to increase by up to 7%, whereas SPEI-based maximum drought severity is projected in future

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Table S2. List of SWAT parameters calibrated in the URB

Category	Parameter	Definition
Snow (.sno)	SUB_SFTMP	Snowfall temperature
	SUB_SMTMP	Snow melt base temperature
	SUB_SMFMX	Melt factor for snow on June 21
	SUB_SMFMN	Melt factor for snow on December 21
	SUB_TIMP	Snowpack temperature lag factor
Groundwater (.gw)	GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur
	GW_REVAP	Groundwater "revap" coefficient
	REVAPMN	Threshold depth of water in the shallow aquifer for "revap" or percolation to the deep aquifer to occur
	GW_DELAY	Delay time
	RCHRG_DP	Deep aquifer percolation fraction
	ALPHA_BF	Baseflow alpha factor
	GW_SPYLD	Specific yield of the shallow aquifer
Management (.mgt)	CN2	Initial SCS runoff curve number for moisture condition II
Hydrologic Response Unit (.hru)	ESCO	Soil evaporation compensation factor
	OV_N	Manning's "n" value for overland flow
	EPCO	Plant uptake compensation factor
	LAT_TTIME	Lateral flow travel time
Soil (.sol)	SOL_AWC	Available water capacity of the soil layer
	SOL_K	Saturated hydraulic conductivity
Routing (.rte)	CH_K2	Effective hydraulic conductivity in main channel alluvium
Reservoir (.res)	RES_K	Hydraulic conductivity of the reservoir bottom
	EVRSV	Lake evaporation coefficient
	NDTARGR	Number of days to reach target storage from current reservoir storage

Table S3. Trends in climate data (precipitation, minimum temperature, and maximum temperature) in the URB

Time	Scenario	Parameter	p-value	trend	slope
Historical (1981–2005)	Models	pcp	0.44	no trend	–0.58
		tmin	0.00	increasing	0.04
		tmax	0.00	increasing	0.05
Mid-century (2030–2059)	RCP 4.5	pcp	0.45	no trend	–0.71
		tmin	0.00	increasing	0.02
		tmax	0.00	increasing	0.03
	RCP 8.5	pcp	0.23	no trend	0.63
		tmin	0.00	increasing	0.05
		tmax	0.00	increasing	0.06
Late-century (2070–2099)	RCP 4.5	pcp	0.07	no trend	1.29
		tmin	0.69	no trend	0.00
		tmax	0.67	no trend	0.00
	RCP 8.5	pcp	0.52	no trend	–0.48
		tmin	0.00	increasing	0.05
		tmax	0.00	increasing	0.06

scenarios to increase by up to 24% over the historical scenario.

The maximum hydrological drought severity has increased in future scenarios compared to the historical period by an average of 15%. Maximum agricultural drought severity has increased in the future scenarios by up to 33% (in Zone 4 during RCP 4.5 mid-century) and has decreased in all the zones during RCP 8.5 mid-century.

Uncertainty in drought characteristics

Uncertainty in any study generally results from imperfection or lack of knowledge about a particular variable or behavior of a system. In using long-term climate projection data in research, we face three major types of uncertainties: uncertainty

Table S4. Average annual values for precipitation (Precip) and SWAT-generated streamflow (Flow), soil moisture (SM), and potential evapotranspiration (PET) in the URB

Time	Scenario	Parameter	Zone 1	Zone 2	Zone 3	Zone 4
Historical (1981–2005)	Models	Precip (mm)	610.6	465.5	299.3	482.3
		Flow (m^3 s^{-1})	3.1	0.9	5.2	0.3
		PET (mm)	1038.4	1045.1	1284.3	1165.9
		SM (mm)	925.3	535.2	818.2	2691.0
Mid-century (2030–2059)	RCP 4.5	Precip (mm)	729.8	480.9	304.7	537.4
		Flow (m^3 s^{-1})	4.1	0.5	6.6	0.5
		PET (mm)	1152.8	1220.8	1449.4	1309.9
		SM (mm)	898.2	462.4	751.7	2534.7
	RCP 8.5	Precip (mm)	728.5	481.2	304.9	537.8
		Flow (m^3 s^{-1})	4.0	0.4	6.5	0.5
		PET (mm)	1163.9	1230.8	1461.8	1318.3
		SM (mm)	870.5	446.0	710.7	2400.7
Late-century (2070–2099)	RCP 4.5	Precip (mm)	737.8	487.0	309.0	543.4
		Flow (m^3 s^{-1})	4.1	0.4	6.7	0.5
		PET (mm)	1181.7	1247.6	1478.4	1336.2
		SM (mm)	869.7	449.0	738.0	2403.7
	RCP 8.5	Precip (mm)	766.5	506.1	324.0	565.2
		Flow (m^3 s^{-1})	4.3	0.4	7.1	0.5
		PET (mm)	1293.4	1356.6	1595.2	1449.9
		SM (mm)	816.8	433.9	769.3	2349.3

Table S5. SWAT model calibration performance at various streamflow calibration locations in the URB

	Nash-Sutcliffe Efficiency		Percent Bias	
Locations	Calibration (1999–2008)	Validation (2009–2018)	Calibration (1999–2008)	Validation (2009–2018)
14020000	0.72	0.72	–7.4	–7.5
MYKO	0.72	0.75	–32.3	–32.4
MCKO	0.98	0.99	2.8	1.1
14020300	0.72	0.67	–21.3	–26.5
14020990	0.65	0.61	–2.6	–34.8
14025000	0.61	0.71	–48	–32.7
14020850	0.76	0.74	–9.8	–16.6
14021000	0.74	0.72	–17.2	–25
14032000	0.47	0.42	–18.3	29.1
14029780	0.98	0.99	4.11	2.33
14031050	0.63	0.77	–23	–24.6
14033500	0.55	0.74	–29.5	–23.8
CS STARG	0.85	0.75	12.13	–7.97
MCKAY STARG	0.56	0.48	10.8	–3.5

in future emissions, uncertainty in the climate system's response to the climate forcing, and uncertainty due to internal variability in the climate system. In this study, we have used various measures to reduce the uncertainty of the drought characteristics of the URB.

The study uses two Representative Concentration Pathways based on the IPCC Fifth Assessment Report (AR5): RCP 4.5 and RCP 8.5. Similarly, statistically downscaled climate data for ten CMIP5 GCMs have been used in the analysis. A previous study by Ahmadalipour et al. (2017) found these models more representative than other GCMs in the CRB. SWAT has been chosen as the hydrologic model with adequate process representation. Model parameters in SWAT were calibrated for flow in the stream for improved representation of the hydrologic processes. Results have been computed at the sub-basin scale and presented on the sub-basin as well as the zonal scale to communicate the results and associated uncertainties to the scientific community, stakeholders, and decision-makers in the basin.

Table S6. Time for drought propagation in the URB (in months) from meteorological to hydrological and agricultural droughts

Time period	Zone	SSI	SSMI
Historical (1981–2005)	Zone 1	5	7
	Zone 2	9	5
	Zone 3	4	10
	Zone 4	8	14
Mid Century (2030–2059) RCP 4.5	Zone 1	4 (−20%)	5 (−29%)
	Zone 2	10 (+11%)	4 (−20%)
	Zone 3	4 (−0%)	9 (−10%)
	Zone 4	8 (−0%)	14 (−0%)
Mid Century (2030–2059) RCP 8.5	Zone 1	4 (−20%)	5 (−29%)
	Zone 2	10 (+11%)	4 (−20%)
	Zone 3	4 (−0%)	9 (−10%)
	Zone 4	8 (−0%)	12 (−14%)
Late Century (2070–2099)RCP 4.5	Zone 1	4 (−20%)	5 (−29%)
	Zone 2	10 (+11%)	4 (−20%)
	Zone 3	4 (−0%)	9 (−10%)
	Zone 4	7 (−13%)	12 (−14%)
Late Century (2070–2099) RCP 8.5	Zone 1	4 (−20%)	5 (−29%)
	Zone 2	10 (+11%)	4 (−20%)
	Zone 3	4 (−0%)	10 (−0%)
	Zone 4	8 (−0%)	13 (−7%)

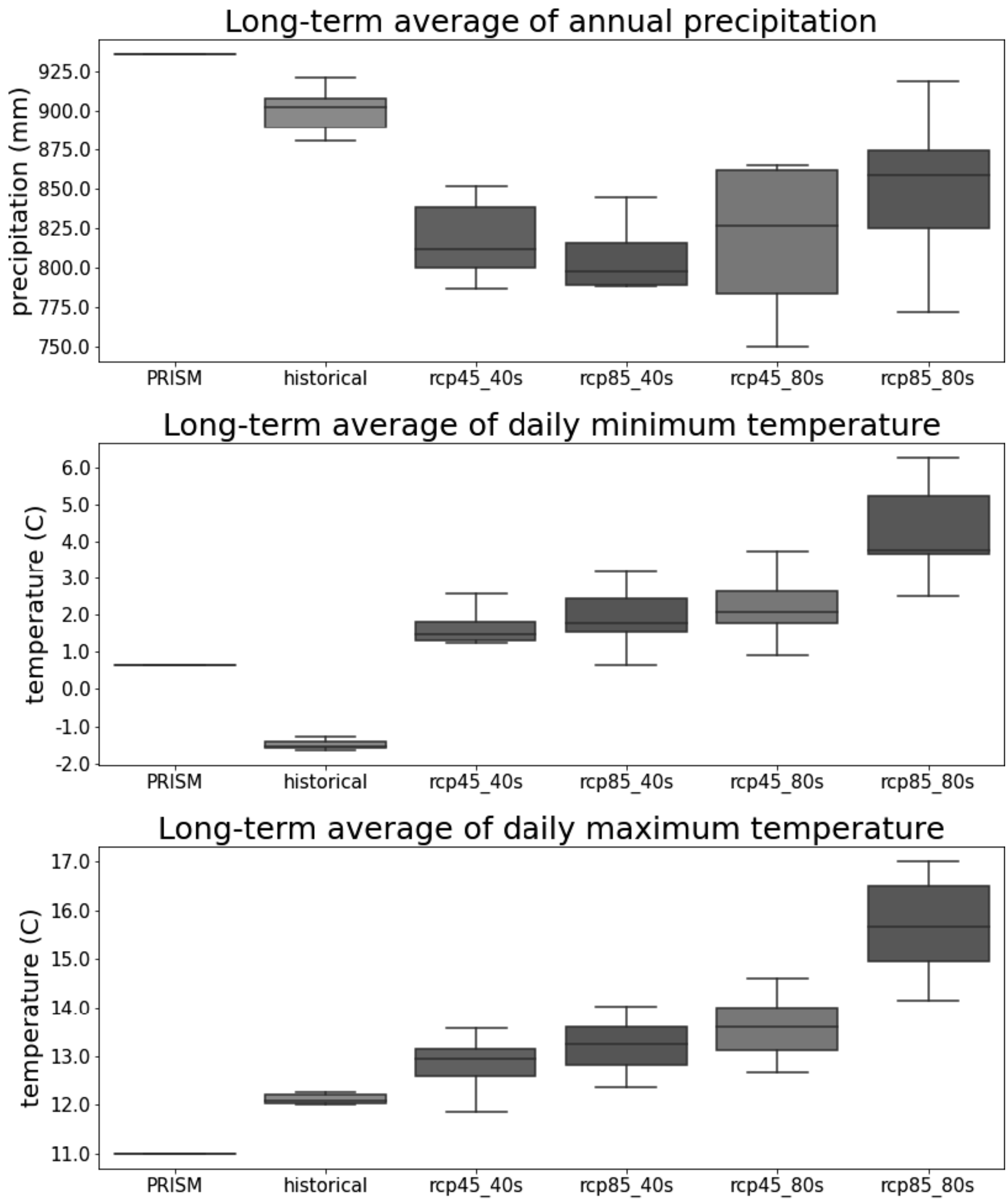

Fig. S1. Long-term climate characteristics in the URB.

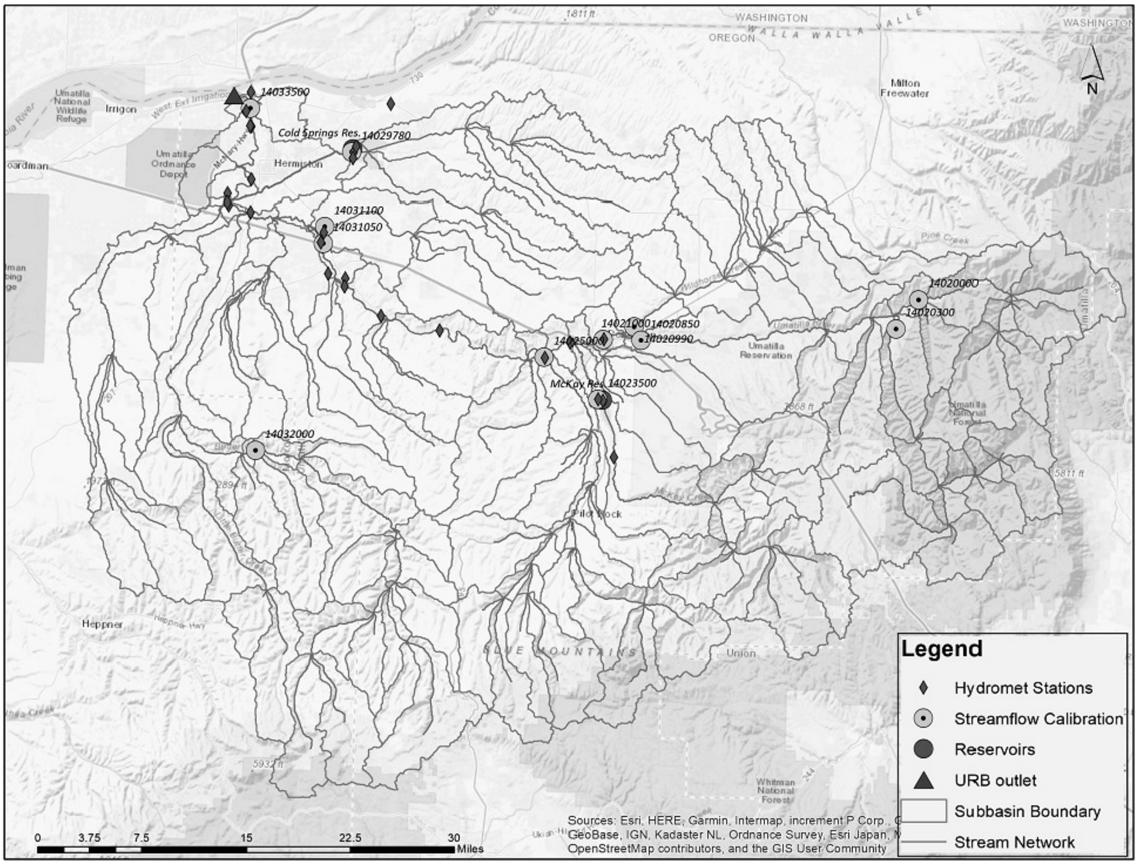

Fig. S2. Location of the hydromet and streamflow calibration stations in the URB along with the 147 sub-basins delineated using SWAT

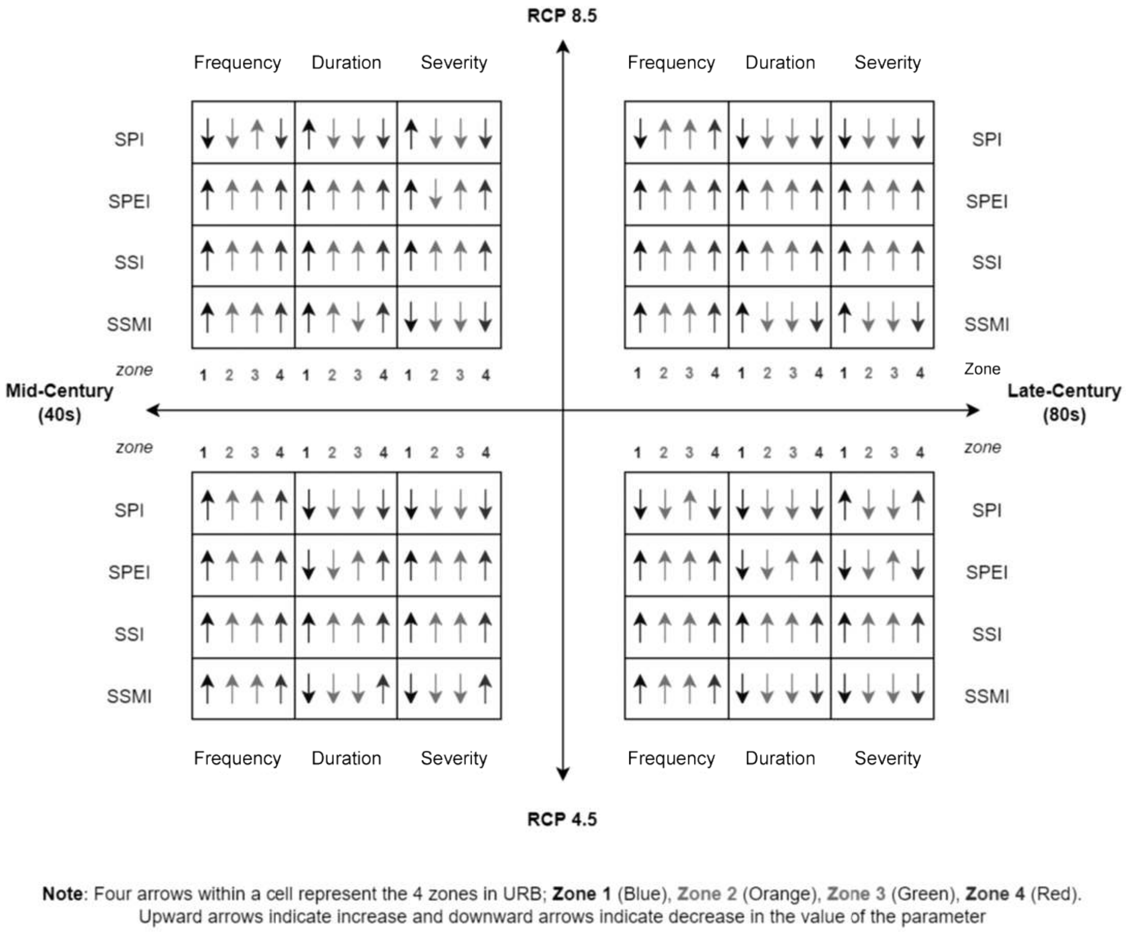

Fig. S3. Summary of projected mid-century and late-century drought characteristics in the URB compared to the historical time period

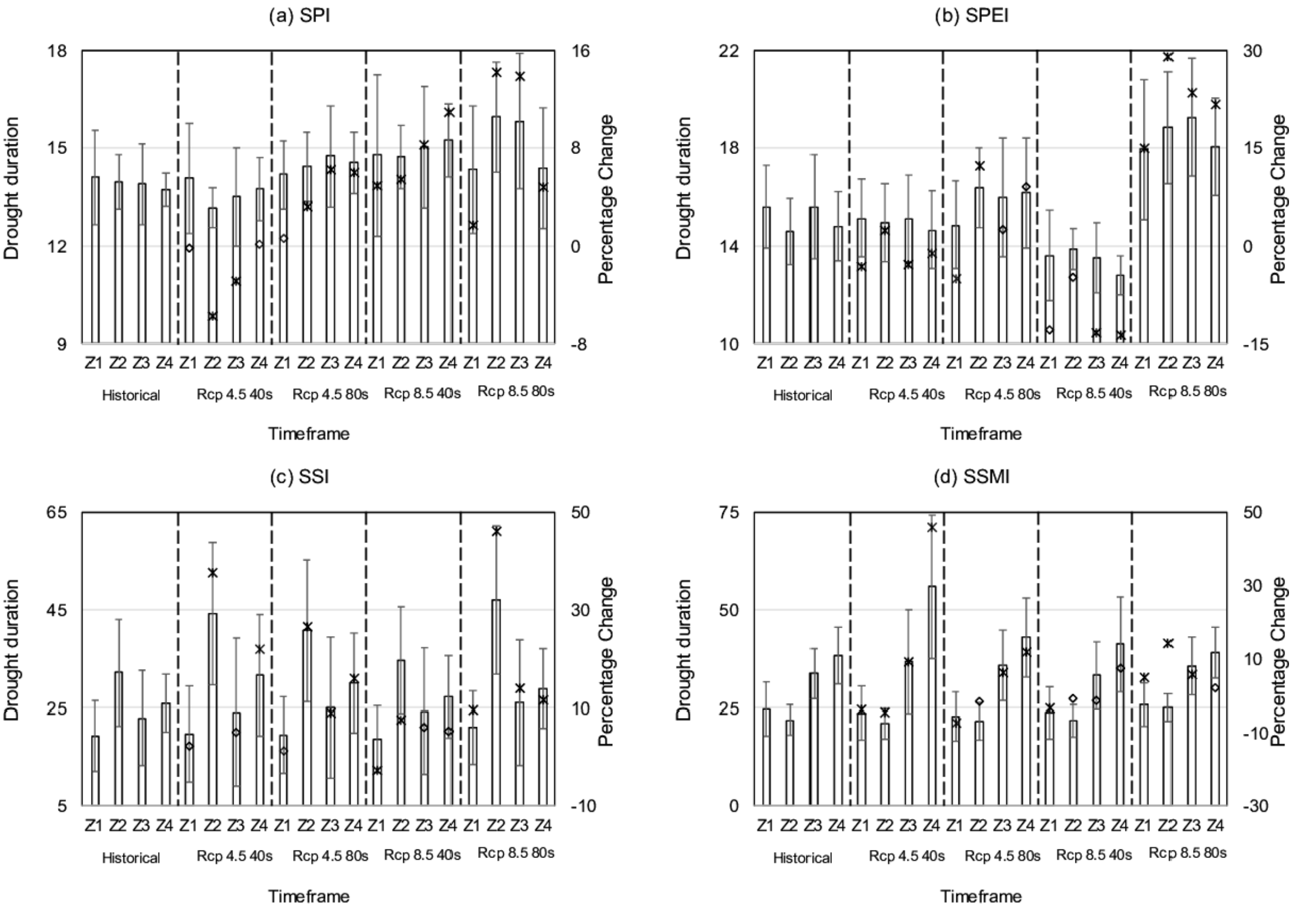

Fig. S4. Summary of maximum drought durations (months per drought) expressed as bars plots (mean) with error bars (std. dev.) for different scenarios in the URB. The secondary *y*-axis represents the percentage change relative to the historical time period. The changes represented by an asterisk symbol were found to be statistically significant at a 5% significance level whereas the changes represented by a diamond symbol were not statistically significant.

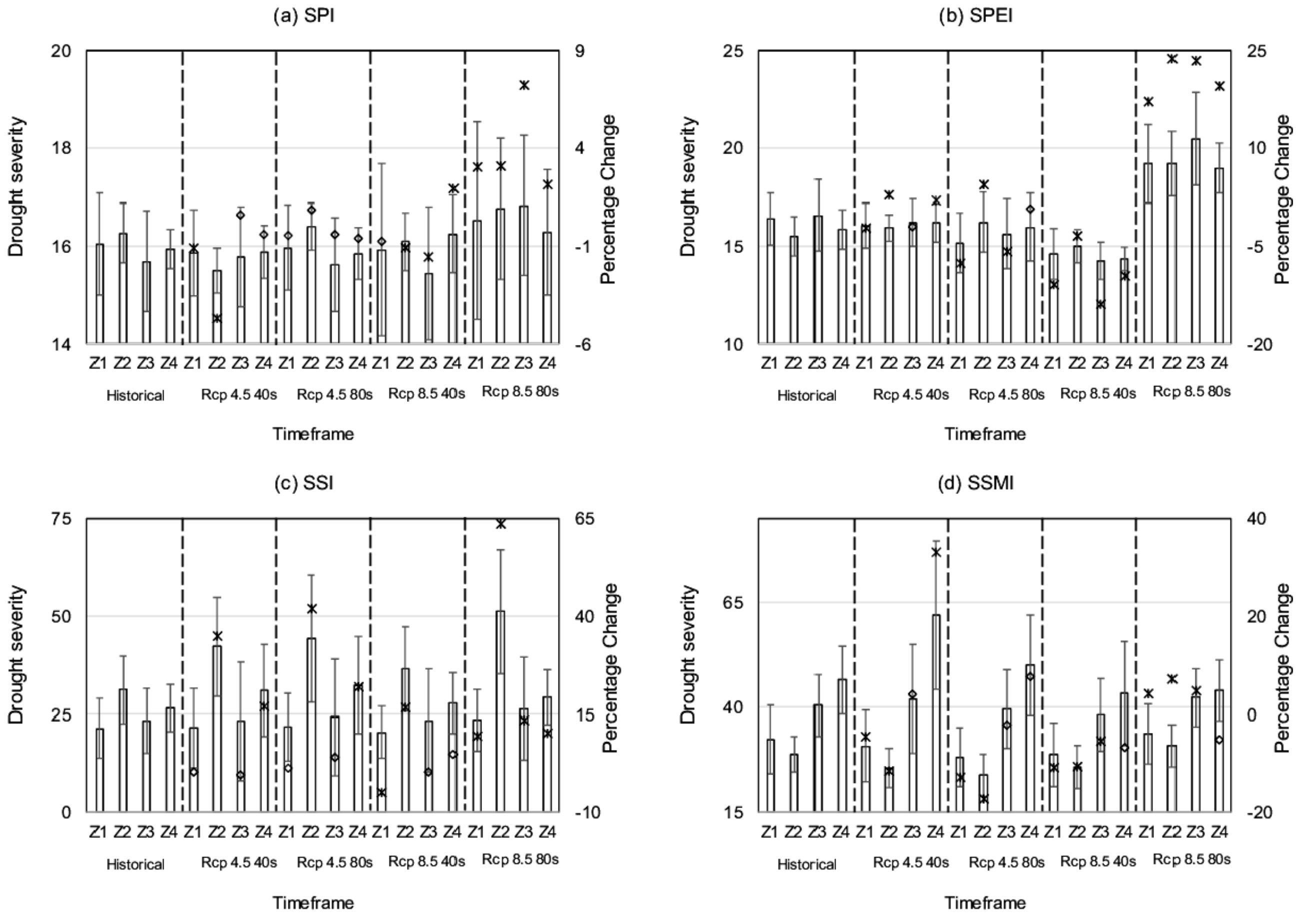

Fig. S5. Summary of maximum drought severities (severity per drought) expressed as bars plots (mean) with error bars (std. dev.) for different scenarios in the URB. The secondary *y*-axis represents the percentage change relative to the historical time period. The changes represented by an asterisk symbol were statistically significant at a 5% significance level, whereas the changes represented by a diamond symbol were not statistically significant.

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