

Earth's Future

RESEARCH ARTICLE

10.1029/2023EF003987

Key Points:

- Warming causes declines in soil moisture in the Mediterranean and Western North America
- The probability of a moderate soil moisture drought increases during both low and high precipitation anomalies, even at 1°C of warming
- The ability of large positive precipitation anomalies to terminate soil moisture droughts will be substantially reduced in a warmer world

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Nielsen, M., Cook, B. I., Marvel, K., Ting, M., & Smerdon, J. E. (2024). The changing influence of precipitation on soil moisture drought with warming in the Mediterranean and Western North America. *Earth's Future*, 12, e2023EF003987. <https://doi.org/10.1029/2023EF003987>

Received 2 AUG 2023

Accepted 4 MAR 2024

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The Changing Influence of Precipitation on Soil Moisture Drought With Warming in the Mediterranean and Western North America

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Abstract Anthropogenic climate change has already affected drought severity and risk across many regions, and climate models project additional increases in drought risk with future warming. Historically, droughts are typically caused by periods of below-normal precipitation and terminated by average or above-normal precipitation. In many regions, however, soil moisture is projected to decrease primarily through warming-driven increases in evaporative demand, potentially affecting the ability of negative precipitation anomalies to cause drought and positive precipitation anomalies to terminate drought. Here, we use climate model simulations from Phase Six of the Coupled Model Intercomparison Project (CMIP6) to investigate how different levels of warming (1, 2, and 3°C) affect the influence of precipitation on soil moisture drought in the Mediterranean and Western North America regions. We demonstrate that the same monthly precipitation deficits (25th percentile relative to a preindustrial baseline) at a global warming level of 2°C increase the probability of both surface and rootzone soil moisture drought by 29% in the Mediterranean and 32% and 6% in Western North America compared to the preindustrial baseline. Furthermore, the probability of a dry (25th percentile relative to a preindustrial baseline) surface soil moisture month given a high (75th percentile relative to a preindustrial baseline) precipitation month is 6 (Mediterranean) and 3 (Western North America) times more likely in a 2°C world compared to the preindustrial baseline. For these regions, warming will likely increase the risk of soil moisture drought during low precipitation periods while simultaneously reducing the efficacy of high precipitation periods to terminate droughts.

Plain Language Summary Regional warming associated with climate change is already making droughts worse in many places. This trend is expected to continue as global temperatures increase in response to continued emissions of greenhouse gases. With increasing temperatures, soils are projected to lose water to the atmosphere as it draws more and more moisture from the land surface, increasing drought risk. At the same time, climate change is also projected to shift precipitation patterns. This means it is important to understand how changes in rainfall will cause and end droughts in the future. Using state-of-the-art climate models, we investigate how future warming will impact the influence of precipitation on soil moisture in the Mediterranean and Western North America. Our results suggest that current levels of monthly precipitation will be insufficient to alleviate drought conditions in a warmer world.

1. Introduction

Anthropogenic climate change has already affected the global hydrological cycle (Durack et al., 2012; Marvel & Bonfils, 2013; Marvel et al., 2019; Zhang et al., 2020), and many regions are already experiencing longer and more intense agricultural and ecological droughts as a result (Field et al., 2012; Seneviratne et al., 2021). Climate models project additional increases in drying and extreme droughts across many regions by 2100 (Cook et al., 2014, 2020). While changes in precipitation and its effect on drought are expected to be highly regionally and locally specific, these large-scale increases in drought severity and risk are predominantly caused by the effects of temperature through the direct effects of warming on increasing evaporative demand (Basara et al., 2019; García-Herrera et al., 2019; Seager et al., 2015; Williams et al., 2014, 2020) and declining snow and runoff efficiency (Dai et al., 2018; Marvel et al., 2021; Vicente-Serrano et al., 2020; Wanders et al., 2015).

Coupled with expected temperature changes, climate change will also affect future precipitation characteristics, including total amounts (Dore, 2005; Held & Soden, 2006), distribution (Marvel & Bonfils, 2013), variability (Pendergrass et al., 2017), event frequency (Papalexiou & Montanari, 2019), and event intensity (Huang et al., 2020; Min et al., 2011). Historically, precipitation is the primary driver of soil moisture drought dynamics (e.g., Seager et al., 2019). Moisture deficits associated with extended periods of reduced precipitation propagate through the hydrological cycle, reducing water availability in soils, streams, and reservoirs (Mishra & Singh, 2010). Conversely, large positive precipitation anomalies are the major cause of drought terminations, supplying the moisture needed to overcome existing surface moisture deficits. In many cases, such drought terminations can be abrupt and disruptive when the precipitation causing the termination is connected to extreme phenomena (e.g., atmospheric rivers, tropical cyclones) (Dettinger, 2013) or is unpredictable on seasonal time scales (Seager, Nakamura, & Ting, 2019). In March of 2023, for example, California experienced two large-scale atmospheric river events that caused dangerous and near-record-breaking flooding (Cassidy, 2023) even as they provided critical drought relief to the region (Santorelli & Moore, 2023). Wet winters in 2016 and 2019 had similar effects (Swain et al., 2018), but importantly drought termination in response to extreme rainfall is not always guaranteed (J. Wu & Dirmeyer, 2020).

Despite these historical examples, it is unclear if historical relationships between precipitation and drought will remain the same under future warming and associated shifts in the hydrological cycle. For example, atmospheric rivers are historically responsible for terminating 33%–74% of US West Coast droughts (Dettinger, 2013), but projected increases of “rain on snow” events in the region's high-altitude mountains could reduce their drought-busting potential (Payne et al., 2020). Increases in precipitation intensity can make it more difficult to terminate droughts if the infiltration capacity of the soils is exceeded (Gimbel et al., 2016; Mayor et al., 2019), while reductions in precipitation frequency can increase soil moisture droughts (Mimeau et al., 2021) because soils have more time to dry out between precipitation events. Even absent any precipitation changes, the effect of warmer temperatures and increases in evaporative demand on soil moisture levels may make it easier to generate a drought and more difficult to terminate one (Cook et al., 2014; Seneviratne et al., 2021).

We use climate model simulations from Phase Six of the Coupled Model Intercomparison Project (CMIP6) to investigate how the effect of low and high monthly precipitation anomalies affect soil moisture drought under different warming levels in the Mediterranean and Western North America reference regions (Iturbide et al., 2020). While these two regions have historically different drought dynamics (Dai & Zhao, 2017; Greve et al., 2014; Kim & Raible, 2021), both regions are already experiencing increases in the length and severity of droughts in the 20th and early 21st century due to climate change (Seager et al., 2014; Seager, Osborn, et al., 2019; Williams et al., 2022). They are also among the regions expected with at least “medium confidence” to experience increased agricultural or ecological drought at 2°C of warming in the most recent Intergovernmental Panel on Climate Change (IPCC) Working Group I report (Seneviratne et al., 2021). We thus investigate the physical dynamics in these regions that influence the cascading impacts of, and relationships between, precipitation and soil moisture drying by asking: (a) How does surface and rootzone soil moisture respond to precipitation anomalies of different magnitude under different warming levels? (b) How likely are different soil moisture anomalies to occur in response to a given precipitation anomaly, again under different levels of warming?

2. Materials and Methods

2.1. CMIP6 Multi-Model Ensemble

We use historical simulations (1850–2014) and a high-end forcing scenario (2015–2100; SSP5-8.5) from Tier 1 of the Shared Socioeconomic Pathway simulation in ScenarioMIP (O'Neill et al., 2016) from the CMIP6 archive (Eyring et al., 2016). This high-end forcing scenario is selected not for realism or likelihood, but to allow us to sample from a range of future global warming levels (1, 2, and 3°C above preindustrial) (Hausfather & Peters, 2020; Hausfather et al., 2022). Our 19 multi-model ensemble (summarized in Table 1) includes models with continuous ensemble members from the historical simulations through the SSP5-8.5 scenario that provide precipitation (pr), surface soil moisture (mrsos), and layer-by-layer column soil moisture (mrsol).

Across the CMIP6 models, particularly in southwestern North America, there is a large divergence in soil moisture content under warming with some models presenting drier, while other models are substantially less dry or show soil moisture wetting (Cook et al., 2021). We use, in equal numbers, models from both the high-risk, dry

Table 1
Models in the Multi-Model Phase Six of the Coupled Model Intercomparison Project (CMIP6) Ensemble. Including the Ensemble Members' Names, and References for the Simulation Contributions to CMIP6

Model	Ensemble count	Ensemble members	Maximum soil depth (m)	Reference
ACCESS-CM2	1	r1i1p1f1	4.6	Dix et al. (2019a, 2019b)
ACCESS-ESM1-5	3	r1i1p1f1, r2i1p1f1, r3i1p1f1	4.6	Ziehn et al. (2019a, 2019b)
BCC-CSM2-MR	1	r1i1p1f1	3.8	T. Wu et al. (2018), Xin et al. (2019)
CanESM5	40	r10i1p1f1, r10i1p2f1, r11i1p1f1, r11i1p2f1, r12i1p1f1, r12i1p2f1, r13i1p1f1, r13i1p2f1, r14i1p1f1, r14i1p2f1, r15i1p1f1, r15i1p2f1, r16i1p1f1, r16i1p2f1, r17i1p1f1, r17i1p2f1, r18i1p1f1, r18i1p2f1, r19i1p1f1, r19i1p2f1, r20i1p1f1, r20i1p2f1, r21i1p1f1, r21i1p2f1, r22i1p1f1, r22i1p2f1, r23i1p1f1, r23i1p2f1, r24i1p1f1, r24i1p2f1, r25i1p1f1, r25i1p2f1, r26i1p1f1, r26i1p2f1, r27i1p1f1, r27i1p2f1, r28i1p1f1, r28i1p2f1, r29i1p1f1, r29i1p2f1, r30i1p1f1, r30i1p2f1, r31i1p1f1, r31i1p2f1, r32i1p1f1, r32i1p2f1, r33i1p1f1, r33i1p2f1, r34i1p1f1, r34i1p2f1, r35i1p1f1, r35i1p2f1, r36i1p1f1, r36i1p2f1, r37i1p1f1, r37i1p2f1, r38i1p1f1, r38i1p2f1, r39i1p1f1, r39i1p2f1, r40i1p1f1, r40i1p2f1, r41i1p1f1, r41i1p2f1, r42i1p1f1, r42i1p2f1, r43i1p1f1, r43i1p2f1, r44i1p1f1, r44i1p2f1, r45i1p1f1, r45i1p2f1, r46i1p1f1, r46i1p2f1, r47i1p1f1, r47i1p2f1, r48i1p1f1, r48i1p2f1, r49i1p1f1, r49i1p2f1, r50i1p1f1, r50i1p2f1, r51i1p1f1, r51i1p2f1, r52i1p1f1, r52i1p2f1, r53i1p1f1, r53i1p2f1, r54i1p1f1, r54i1p2f1, r55i1p1f1, r55i1p2f1, r56i1p1f1, r56i1p2f1, r57i1p1f1, r57i1p2f1, r58i1p1f1, r58i1p2f1, r59i1p1f1, r59i1p2f1, r60i1p1f1, r60i1p2f1	4.1	Swart et al. (2019a, 2019b)
CESM2	3	r10i1p1f1, r11i1p1f1, r4i1p1f1	8.6	Danabasoglu (2019a, 2019b)
CESM2-WACCM	5	r1i1p1f1, r2i1p1f1, r3i1p1f1, r4i1p1f1, r5i1p1f1	8.6	Danabasoglu (2019c, 2019d)
CNRM-CM6-1	6	r1i1p1f1, r2i1p1f1, r3i1p1f1, r4i1p1f1, r5i1p1f1, r6i1p1f1	12	Voldoire (2018, 2019a)
CNRM-ESM2-1	5	r1i1p1f1, r2i1p1f1, r3i1p1f1, r4i1p1f1, r5i1p1f1	12	Seferian (2018, 2019b)
GISS-E2-1-G	9	r1i1p3f1, r1i1p5f1, r2i1p3f1, r2i1p5f1, r3i1p3f1, r3i1p5f1, r4i1p3f1, r4i1p5f1, r5i1p3f1	2.7	NASA Goddard Institute for Space Studies (2018), Studies (NASA/GISS), (2020)
IPSL-CM6A-LR	6	r14i1p1f1, r1i1p1f1, r2i1p1f1, r3i1p1f1, r4i1p1f1, r6i1p1f1	65.6	Boucher et al. (2018, 2019)
KACE-1-0-G	3	r2i1p1f1, r3i1p1f1, r1i1p1f1	3	Byun, Lim, Sung, et al. (2019), Byun, Lim, Shim, et al. (2019)
MIROC6	50	r10i1p1f1, r11i1p1f1, r12i1p1f1, r13i1p1f1, r14i1p1f1, r15i1p1f1, r16i1p1f1, r17i1p1f1, r18i1p1f1, r19i1p1f1, r20i1p1f1, r21i1p1f1, r22i1p1f1, r23i1p1f1, r24i1p1f1, r25i1p1f1, r26i1p1f1, r27i1p1f1, r28i1p1f1, r29i1p1f1, r30i1p1f1, r31i1p1f1, r32i1p1f1, r33i1p1f1, r34i1p1f1, r35i1p1f1, r36i1p1f1, r37i1p1f1, r38i1p1f1, r39i1p1f1, r40i1p1f1, r41i1p1f1, r42i1p1f1, r43i1p1f1, r44i1p1f1, r45i1p1f1, r46i1p1f1, r47i1p1f1, r48i1p1f1, r49i1p1f1, r50i1p1f1, r51i1p1f1, r52i1p1f1, r53i1p1f1, r54i1p1f1, r55i1p1f1, r56i1p1f1, r57i1p1f1, r58i1p1f1, r59i1p1f1, r60i1p1f1	9	Tatebe and Watanabe (2018), Shiogama et al. (2019)
MPI-ESM1-2-HR	2	r1i1p1f1, r2i1p1f1	9.834	Jungclaus et al. (2019), Schupfner et al. (2019), Steger et al. (2019)
MPI-ESM1-2-LR	11	r10i1p1f1, r11i1p1f1, r12i1p1f1, r13i1p1f1, r14i1p1f1, r15i1p1f1, r16i1p1f1, r17i1p1f1, r18i1p1f1, r19i1p1f1, r20i1p1f1	9.834	Wieners et al. (2019a, 2019b)
MRI-ESM2-0	2	r1i1p1f1, r2i1p1f1	10	Yukimoto et al. (2019a, 2019b)
	1	r1i1p1f1	8.6	Seland et al. (2019a, 2019b)

Table 1
Continued

Model	Ensemble count	Ensemble members	Maximum soil depth (m)	Reference
NorESM2-LM	1	rl1plf1	8.6	Bentsen et al. (2019a, 2019b)
NorESM2-MM	1	rl1plf1	3.8	Lee and Liang (2020a), Lee and Liang (2020b)
TaiESM1-UKESM1-0-LL	5	rl1plf2, r2ilplf2, r3ilplf2, r4ilplf2, r8ilplf2	3	Good et al. (2019), Tang et al. (2019)

categorization and the low-risk, moderately dry or wetting categorization, as well as models that display a wide range of climate sensitivities.

2.2. Analyses

We investigate the effect of precipitation on surface and rootzone soil moisture. The surface soil moisture (mrsos) diagnostic is the same depth across all models, representing moisture in the top 10 cm of the soil column. We define rootzone soil moisture as the moisture contained in the top 2 m. To estimate this from each model, we linearly interpolate the layer-by-layer soil moisture diagnostic (mrsol) from the surface to two m depth as in Cook et al. (2021).

The surface and rootzone soil moisture are deseasonalized and standardized (z-score) to create monthly soil moisture anomalies, with the late 19th century from the historical simulation serving as our baseline (1861–1880). This anomaly calculation and all subsequent calculations are performed at the individual model and ensemble member level, then averaged so that all ensemble members are equally weighted within each model and all models are also equally weighted. The 1861–1880 baseline provides a reasonable approximation of preindustrial greenhouse gas forcing with low volcanic forcing and is the same length of time (20 years) as the warming level periods calculated in our model ensemble. The IPCC has also adopted this time period as a preindustrial baseline for the last several Special and Assessment Reports (Hoegh-Guldberg et al., 2018). Standardization is performed by subtracting the baseline monthly mean and then dividing by the baseline standard deviation, which is done for each grid cell and each ensemble member. For precipitation (pr), we calculate the standardized precipitation index (SPI) by fitting the data to a gamma distribution calibrated during the baseline (1861–1880) period and then transform the time series into a normal distribution. SPI can be calculated over different periods and for this analysis we use both 1 month and 6 month periods. We tested several SPI periods and found little difference in the relationships between precipitation and soil moisture.

Using the updated IPCC Sixth Assessment Report Working Group 1 reference regions (Iturbide et al., 2020) for the Mediterranean and Western North America regions, we create land-area weighted spatial averages of precipitation, surface soil moisture, and rootzone soil moisture. We then normalize by warming level, grouping all models and members of the ensemble to identify dry and wet conditions. For soil moisture, we define months as “dry” when the monthly anomaly is below the 25th percentile and “wet” when the monthly anomaly is greater than the 75th percentile, both relative to the preindustrial baseline. For precipitation, we use these same percentiles but will refer to the monthly anomalies as “low” and “high.” Analysis of an additional “normal” month, defined as soil moisture or SPI values within the central tercile between the 33rd and 66th percentile is also included in Supporting Information S1. We then calculate the relative probability of soil moisture anomalies and SPI for both conditions across three global warming levels: 1, 2, and 3°C. We use the data provided by Hauser et al. (2021) to find the time at which the global warming level exceeds these thresholds in each model considered.

We calculate the conditional probability of a dry or wet soil moisture month given low or high precipitation conditions. Because surface soil moisture responds relatively rapidly to precipitation surplus or deficit, we use the 1-month SPI to calculate the conditional probability of a wet or dry surface soil moisture month. To compensate for the greater persistence from the larger reservoir in the deeper 2-m column, which is less likely to respond to a brief, monthly change in precipitation, we use a 6-month SPI calculation for the rootzone conditional probabilities.

From the collection of dry and wet months and the SPI time series, we create time series composites (Figures 2 and 6). We first identify months of wet or dry soil moisture, creating composites using 24 months of SPI before and after each wet or dry soil moisture month separately for each warming level. To normalize across warming levels, we adjust the composites so that the period 24 to 12 months prior to the selected soil moisture month have a zero average as a means of better comparing the effect of warming on the relationship between wet or dry soil moisture months and precipitation. This is calculated by subtracting the mean of the SPI values for the period 24 to 12 months preceding the soil moisture dry or wet month from the entire SPI composite. This brings all warming levels in line with

the pre-industrial baseline. The final plots now show only the 12 months preceding and following the dry or wet months.

3. Results

3.1. Mediterranean

Observations, as well as several generations of general circulation models, show a strong signal of historical drying across the Mediterranean region (Cook et al., 2016; Seager et al., 2014; Seager, Osborn, et al., 2019), which persists in CMIP6 model projections (Cook et al., 2020; Ukkola et al., 2020). This current and projected drying signal is attributed to precipitation declines from a poleward expansion of the subtropical dry zones at the descending branch of the Hadley cell (Held & Soden, 2006; Previdi & Liepert, 2007; Seager et al., 2010) and an increase in mean flow moisture divergence (Seager et al., 2014).

Consistent with these previous analyses, Mediterranean precipitation declines with warming in our model ensemble over the 21st century, as does both surface and rootzone soil moisture in all months and seasons (Figure 1). Rootzone soil moisture response is somewhat noisier, with some models projecting larger shifts between the wet winter and dry summer seasons. In aggregate, the ensemble projects the region shifting into a substantially drier mean state in response to warming.

Coincident with the long term drying in the Mediterranean (Figures 2a–2c), we find that the amount of precipitation associated with wet and dry soil moisture events also shifts with warming. Figure 2 shows SPI prior to, during, and after a dry or wet soil moisture month. These time series composites highlight the relationship between discrete soil moisture events and precipitation anomalies. Overall, we find that increasing temperatures require smaller precipitation deficits to trigger a dry soil moisture month, and precipitation must be higher for a longer period of time to achieve wet soil moisture.

During the preindustrial baseline, a dry surface soil moisture anomaly is associated with a large negative (−0.38) SPI during the event month and several months preceding. With increased warming, lower precipitation deficits are associated with both dry surface and dry rootzone soil moisture events (Figures 2d and 2e). At 2°C, the average SPI anomaly during a dry surface soil moisture month is nearly half (−0.21) that during the baseline, while for a rootzone soil moisture event it is approximately a third less. Conversely, even greater precipitation volume is needed at higher global warming levels to achieve wet surface and rootzone soil moisture (Figures 2f and 2g). These results demonstrate that, at higher warming levels, lower precipitation deficits can initiate a soil moisture drought and even higher precipitation anomalies will be necessary to terminate droughts in the Mediterranean.

How likely are such precipitation surpluses or deficits to occur in the Mediterranean as the world warms? We calculate the probability of low and high monthly precipitation at 1, 2, and 3°C of warming (Figure 3). With each additional degree of warming, the probability of a low precipitation month increases while the probability of a high precipitation month decreases, consistent with the overall decreasing precipitation trend in the region (Figures 1a and 1b). This decrease in precipitation, combined with the rising temperatures and evaporative demand, means that both surface and rootzone soil moisture follow the same trend as precipitation: the probability of a dry event increases significantly and the probability of a wet event decreases with warming (Figures 3c–3f). Dry surface soil moisture and rootzone soil moisture months are 2.8 and 3.8 times more likely (median change) to occur under 2°C of warming than during the preindustrial baseline period. By 3°C of warming, dry rootzone soil moisture events (Figure 3e) become even more likely, occurring on average more than 96% of the time. Simultaneously, the probability of wet soil moisture or high precipitation months (Figures 3b, 3d, and 3f) decreases with warming.

Along with changes in the frequency of wet and dry precipitation and soil moisture events, the relationship between precipitation and soil moisture also changes significantly with warming (Figure 4). For example, the average probability of a dry surface soil moisture event following a low precipitation event increases from 71% under preindustrial conditions to 91% with 2°C of warming (Figure 4a), a 29% increase. During the same low precipitation event, the probability of a wet surface soil moisture month remains low with increased warming, with a median value of <1% for 2 and 3°C of warming (Figure 4b). For “normal” precipitation amounts, defined as monthly totals between the 33rd and 66th percentile (central tercile), the median of both surface and dry rootzone soil moisture more than doubles at 2°C compared to the preindustrial baseline (Figures S1a and S1c in

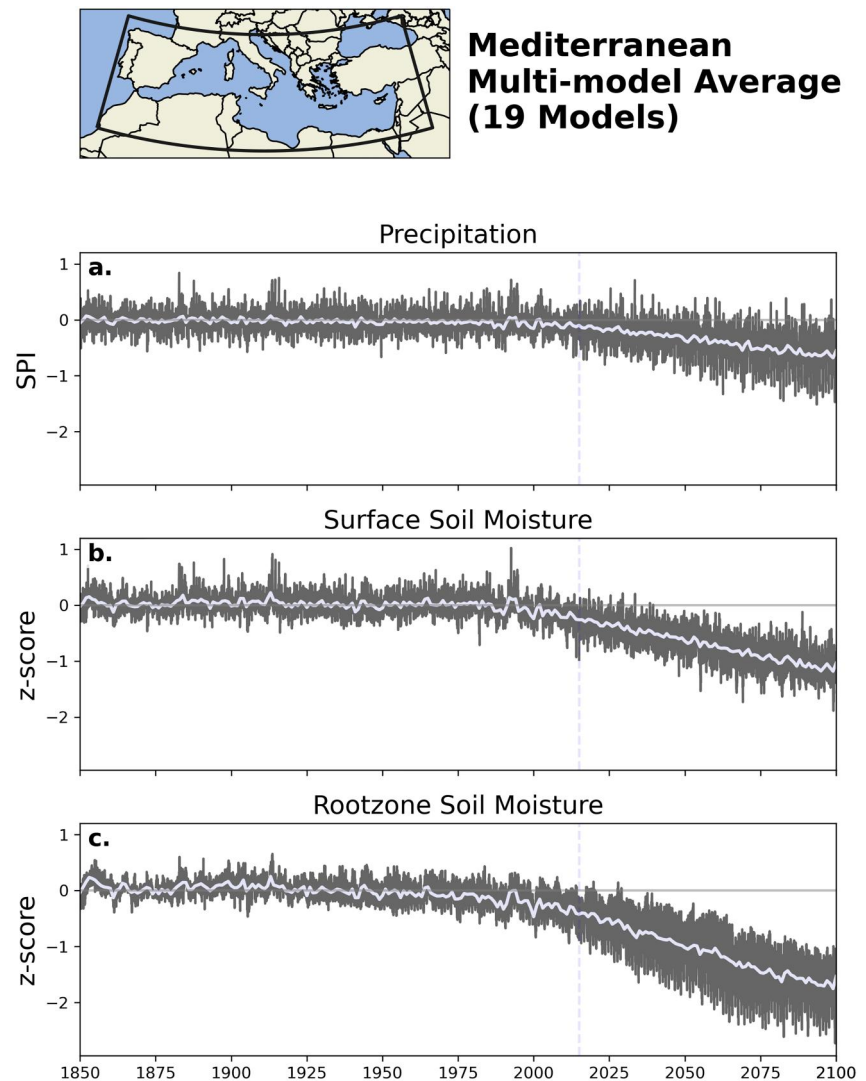


Figure 1. Mediterranean multi-model average time series anomalies. Monthly (gray line) and annual (lavender line) standardized time series of multi-model ensemble anomaly average precipitation (a), surface soil moisture (b), and rootzone soil moisture (c) from the historical (1850–2014) through SSP5-8.5 (2014–2100) experiments. Mean values were determined for the Mediterranean region as defined in Iturbide et al. (2020) for the Intergovernmental Panel on Climate Change Sixth Assessment Report Reference Regions.

Supporting Information S1). In a warmer world, high precipitation events will be less able to moisten soils in the Mediterranean: the median probability of a wet surface soil moisture event given a high precipitation event decreases from 71% in the baseline to 36% at 3°C. At 3°C of warming, the probability that even a high precipitation event will be followed by a dry surface soil moisture event increases eightfold (from 5% to 39%), suggesting that rainfall anomalies considered moderately high events in the baseline case will be insufficient to terminate future droughts.

The trend is similar for rootzone soil moisture given low precipitation. In the rootzone, dry events are all but guaranteed during low precipitation (6-month SPI) at 2 and 3°C of warming: the probability of a dry rootzone soil moisture event given a low precipitation event increases from a mean probability of 75% during the preindustrial baseline to 96% at 2°C and 98% at 3°C (Figure 4c). At 2 and 3°C of warming, the region is extremely unlikely (mean 1.5% and 0.5% respectively) to experience wet rootzone soil moisture during low precipitation periods. For rootzone soil moisture, by 2°C of warming, the probability of a wet rootzone soil moisture event during a high-percentile precipitation event is less than 10% for the majority of models, down from 73% during the baseline

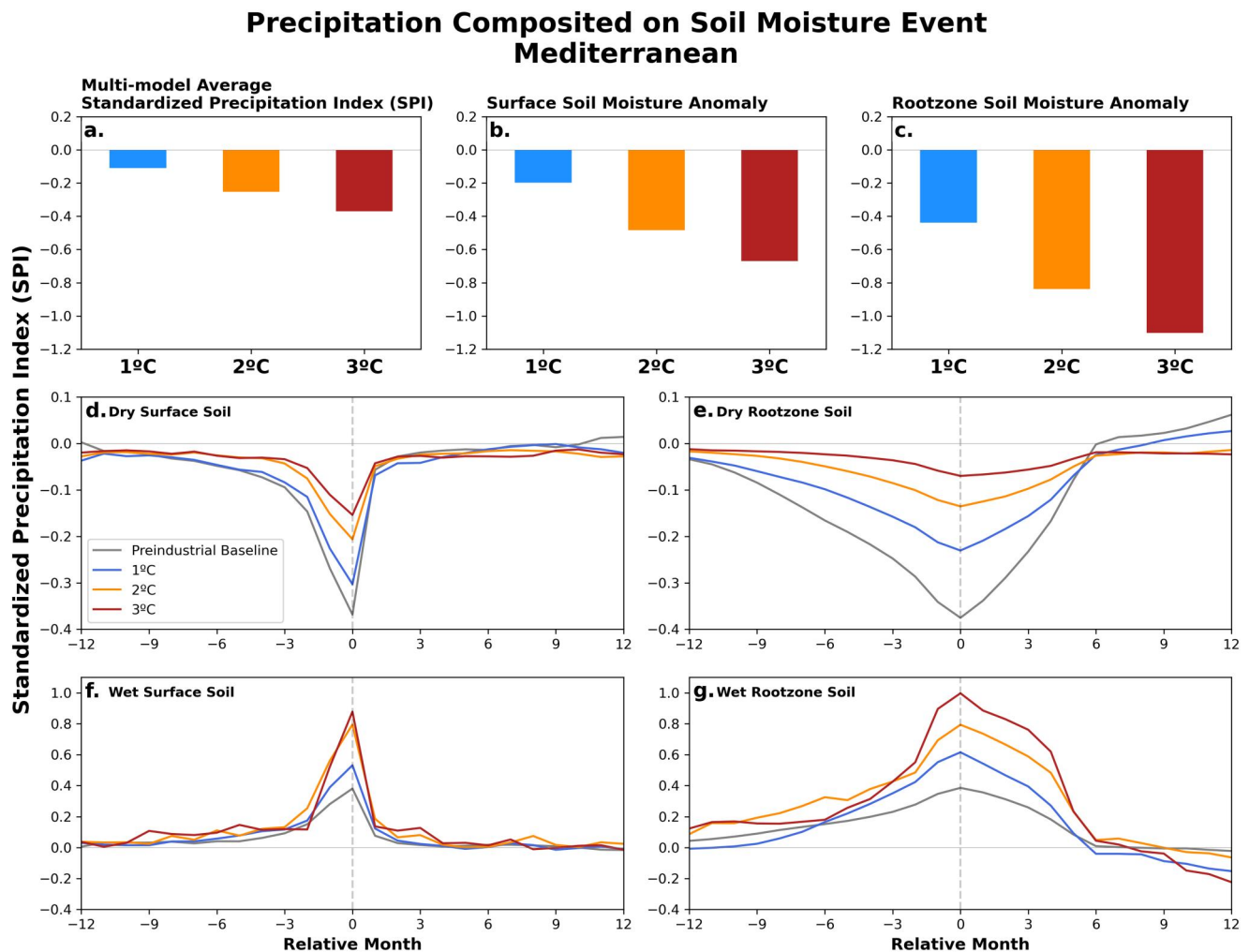


Figure 2. Precipitation composites on dry and wet soil moisture monthly anomalies in the Mediterranean. Multi-model mean state shifts in standardized precipitation index (a), surface soil moisture anomalies (b), and rootzone soil moisture anomalies (c) as well as precipitation composited before, during, and after a low (25th percentile d, e) or high (75th percentile, f, g) surface (d, f) and rootzone (e, g) soil moisture months in the Mediterranean region.

period. And the probability of a dry rootzone during a high-precipitation event is more than 11 times more likely at 2°C of warming. Even down to 2 m, high precipitation has reduced efficacy to terminate and/or prevent moderate drought conditions.

Anomalously high precipitation events capable of terminating future droughts in the aridifying Mediterranean occur far less frequently at 2 or 3°C than during the baseline and 1°C periods. Across the multi-model ensemble, there was an average of 13 moderately wet months of surface soil moisture at 3°C of warming per model member, compared to 60 months during the baseline period. During the baseline period, droughts are less likely during periods of rainfall surplus. In a warmer world, rising temperatures and decreases in precipitation in the region will mean overall drier soils, which will likely require more precipitation to terminate droughts. These results suggest that the observed and projected decreasing trend in precipitation will mean that the Mediterranean will not get enough rainfall to end baseline-level drought conditions in the future, let alone provide the extra surplus precipitation needed to end more severe future droughts.

3.2. Western North America

The last two decades have been the driest period since at least 800 CE across much of Western North America (Williams et al., 2022), with both record high temperatures and low storage in some of the most important surface reservoirs, including Lake Mead and Lake Powell (USBOR, 2023). Compared to the Mediterranean, the Western

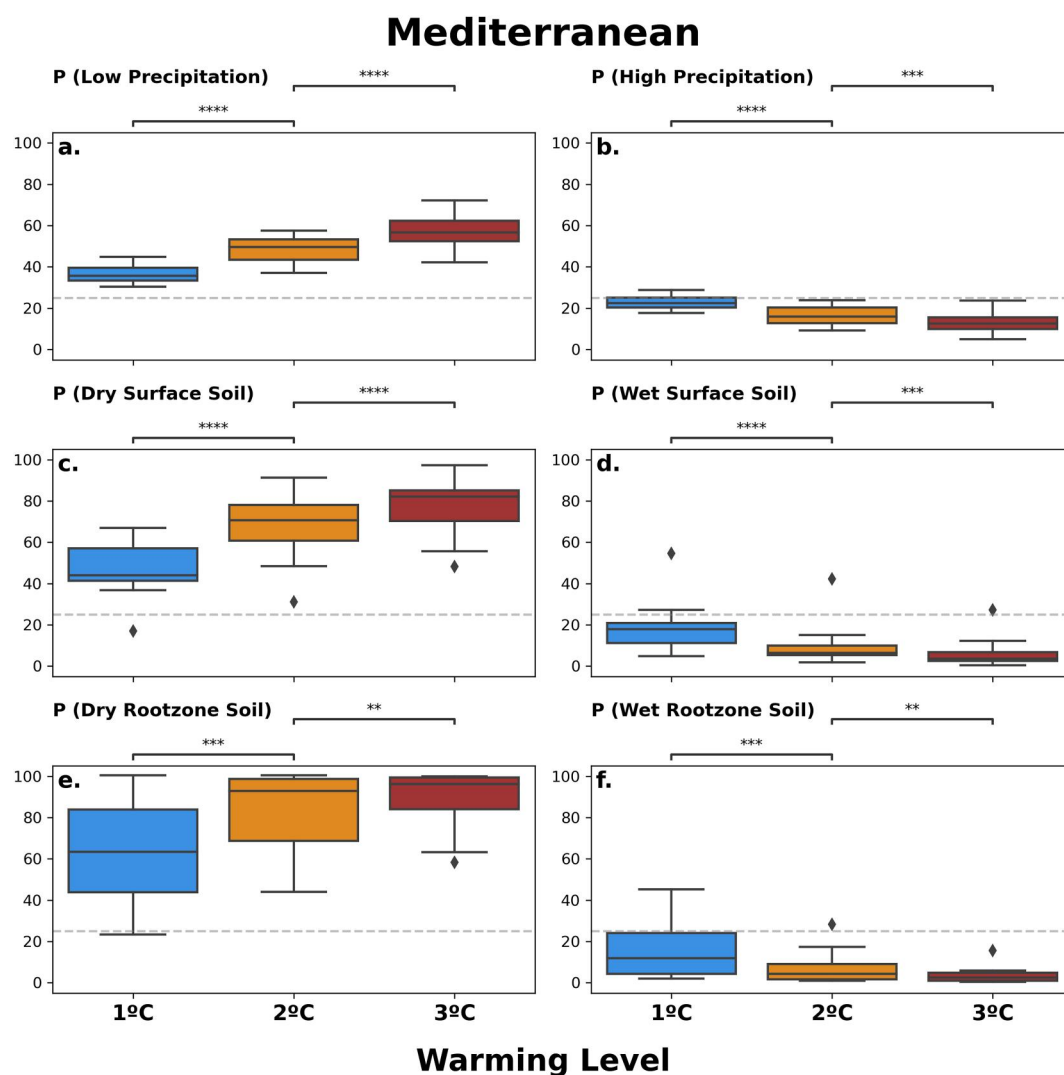


Figure 3. Precipitation, soil moisture and warming relationships in the Mediterranean. Probability of low or dry (25th percentile relative to preindustrial baseline) and high or wet (75th percentile) monthly standardized precipitation index (a, b), surface soil moisture (c, d), and rootzone soil moisture (e, f) anomalies, under three levels of warming in the Mediterranean region. Dotted line is the prescribed 25% probability during the pre-industrial baseline (1861–1880). Significance is calculated using paired samples Wilcoxon tests (Charlier et al., 2022).

North America region that we consider includes more diverse climate regimes from the more temperate Pacific Northwest to the deserts of the US Southwest. As a result, current and projected hydroclimate responses in Western North America are more complex on both the annual and seasonal scales. For continuity, we treat Western North America the same as the Mediterranean in our analysis and pool annual averages across the large region. Model projections for Western North America estimate an overall increase in temperature, evaporative demand, and soil moisture droughts (Cook et al., 2020; Seneviratne et al., 2021; Xu et al., 2019), while precipitation is expected to increase in winter and decline in summer (Gershunov et al., 2019; Marvel et al., 2021). At the same time, snowpack and snowfall is also expected to decline, even in areas where total precipitation (Payne et al., 2020) and extreme precipitation (Gershunov et al., 2019; Huang et al., 2020; Swain et al., 2018) increase.

While there is substantial spread in the projections (Figure 5), particularly near the end of the century, annual average precipitation in the ensemble increases, while annual surface soil moisture decreases. Unlike the Mediterranean, which is projected to aridify with warming, Western North America's moisture supply and demand both appear to be increasing. Annual rootzone soil moisture in the region decreases in the early parts of the 21st century, but seems to recover by the end of the century. Both surface and rootzone soil moisture see increased

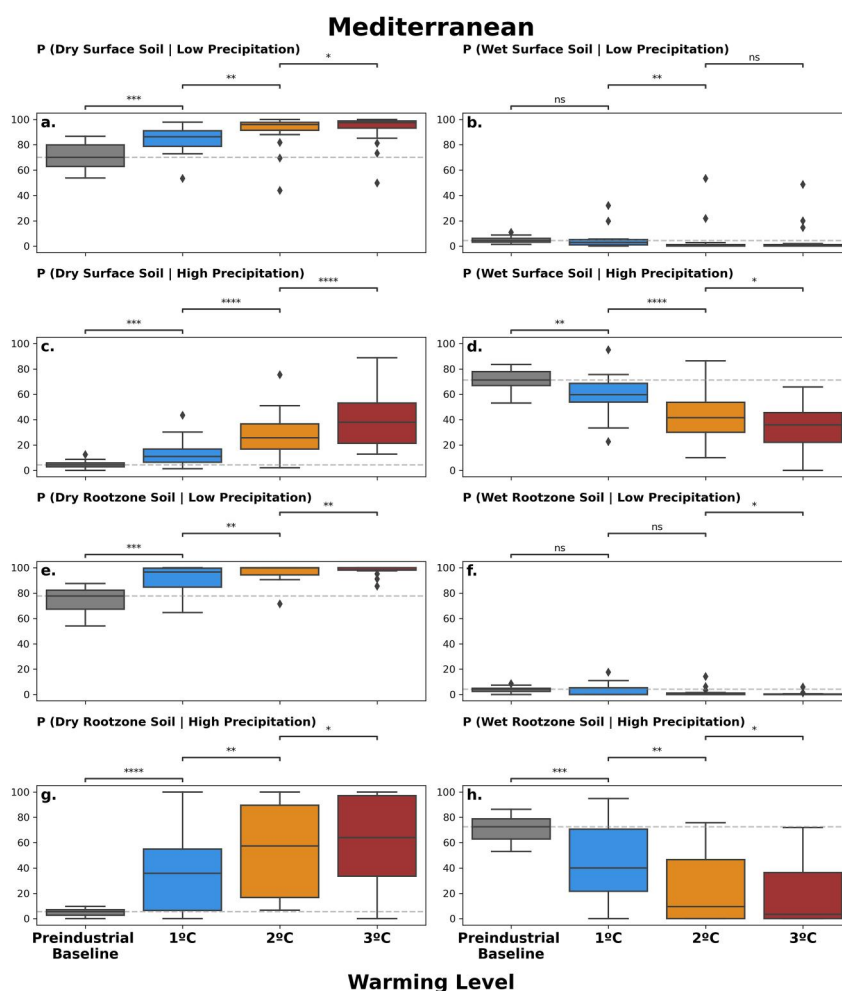


Figure 4. Conditional relationships between precipitation, soil moisture, and warming in the Mediterranean. Conditional probability of a dry (25th percentile relative to preindustrial baseline) or wet (75th percentile) surface soil (a–d) or rootzone soil (e–h) moisture anomaly given a low (25th percentile: a, b, e, f) or high (75th percentile: c, d, g, h) standardized precipitation index. Significance calculated using paired samples Wilcoxon tests (Charlier et al., 2022).

variance in the 21st century relative to the 20th, with the largest negative and positive average z-scores occurring toward the end of the 21st century. End-of-century precipitation increases and rootzone wetting are strongest during the cold months (October–March), in contrast to the Mediterranean which is projected to experience drying across all variables in all seasons (Figure S2 in Supporting Information S1 and Figure 3); this result is in line with other studies of projected seasonal changes in drought metrics (Cook et al., 2020).

As the global warming level increases, SPI increases, and rootzone and surface soil moistures decrease (Figures 6a–6c). The declines in soil moisture anomalies across warming levels are smaller than in the Mediterranean, particularly in the rootzone. Similar to the Mediterranean, smaller precipitation deficits are needed at warmer global warming levels to produce dry surface soil moisture months (Figure 6d) and larger precipitation anomalies are needed to produce wet surface and rootzone soil moisture months (Figures 6f and 6g).

With warming, the probability of low-precipitation months (Figure 7a) declines slightly, but not significantly, and there are modest increases in the probability of high-precipitation months (Figure 7b), consistent with the overall increases in precipitation in Western North America (Figure 5a). Though the probability of high-precipitation monthly anomalies increases in Western North America, drought risk also increases due to increases in evaporative demand: the median probability of a dry surface soil moisture month increases significantly by 88% and 147% at 2 and 3°C of warming relative to the preindustrial baseline, a massive increase in risk of these events. Consistent with these changes, the probability of wet surface soil moisture months also declines, with a significant

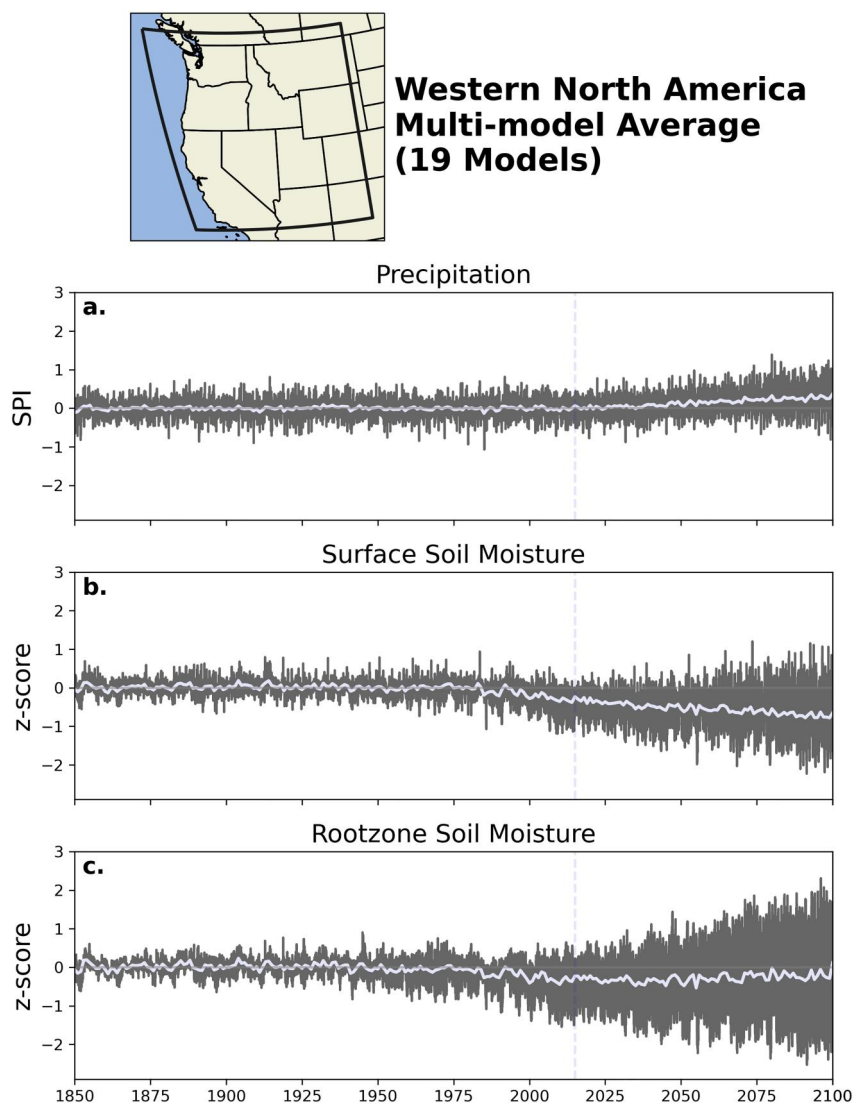


Figure 5. Western North America multi-model average time series anomalies. Monthly (gray line) and annual (lavender line) standardized time series of multi-model ensemble anomaly average precipitation (a), surface soil moisture (b), and rootzone soil moisture (c) from the historical (1850–2014) through SSP5-8.5 (2014–2100) in Western North America. Mean values were determined for the Western North America region as defined in Iturbide et al. (2020) for the Intergovernmental Panel on Climate Change Sixth Assessment Report Reference Regions.

change between 1 and 2°C of warming (Figure 7d). While wet rootzone soil moisture shows no significant change with any warming, dry rootzone soil moisture does increase significantly between the preindustrial baseline and 2 or 3°C (Figures 7e and 7f). As in the Mediterranean, the models project an increase in the probability of dry soil moisture months with warming, but unlike the Mediterranean, high-precipitation months will become more likely in Western North America.

The conditional probability analysis (Figure 8) highlights the complexity of the Western North America hydroclimate response to warming compared to the Mediterranean. In Western North America, we only find consistently significant trends in surface soil moisture responses to precipitation. The mean probability of dry surface soil moisture conditions under both low and high monthly precipitation anomalies increases significantly with warming (Figures 8a and 8c): dry surface soils are 1.3 and 3.3 times more likely during low- and high-precipitation anomalies, respectively, at 2°C of warming, a 32% and 232% increase compared to the baseline probability. Similarly, the median probability of wet surface soil moisture conditions decrease by 77% and 26% during these same precipitation months. In contrast with the Mediterranean, however, changes in rootzone soil

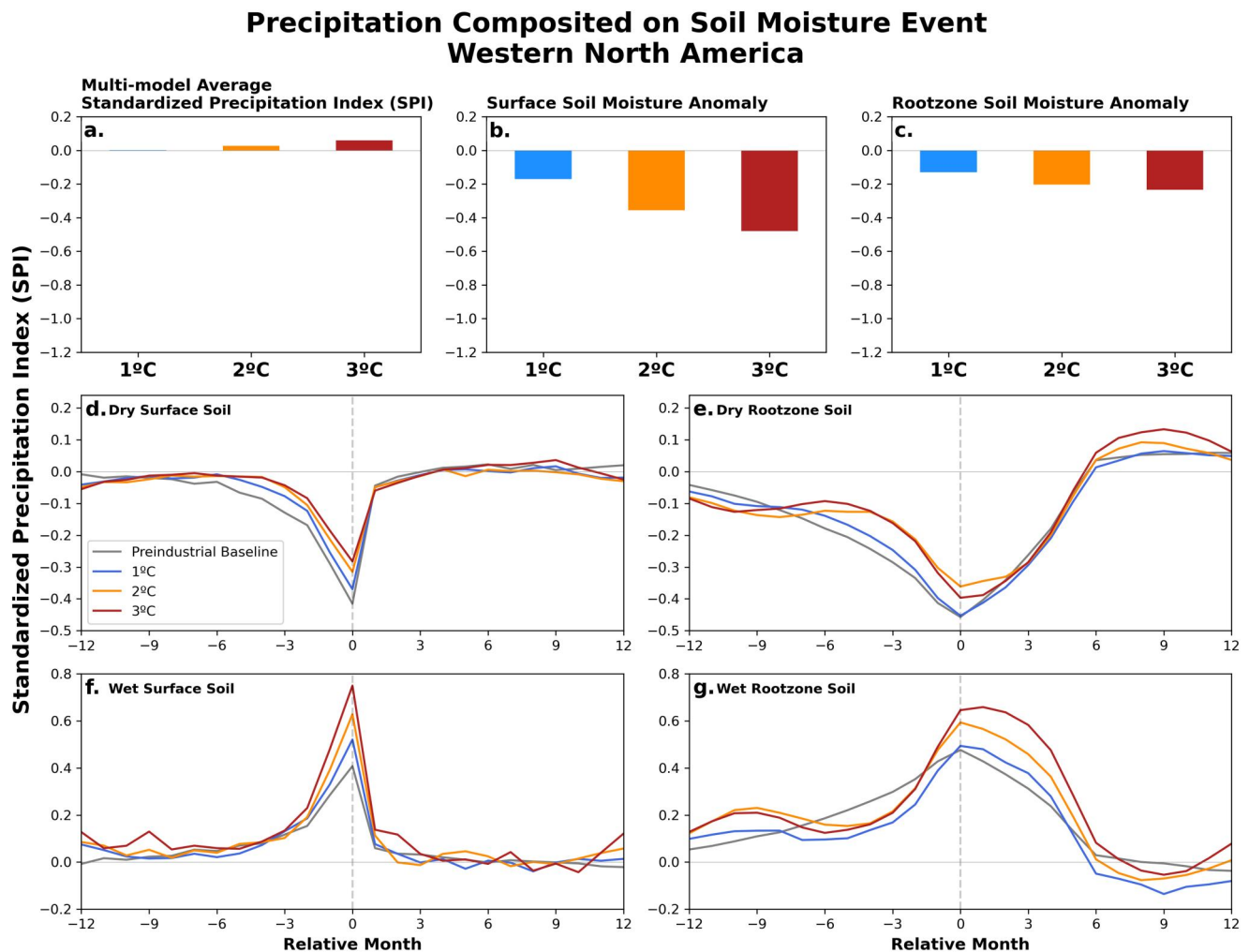


Figure 6. Precipitation composites on dry and wet soil moisture monthly anomalies in Western North America. Multi-model mean state shifts in standardized precipitation index (a), surface soil moisture anomalies (b), and rootzone soil moisture anomalies (c) as well as precipitation composited before, during, and after a low (25th percentile, d, e) or high (75th percentile, f, g) surface (d, f) and rootzone (e, g) soil moisture months in Western North America.

moisture conditional probabilities at incremental increases in warming levels are largely insignificant. The only exception being the probability of dry rootzone soil given high precipitation as temperatures increase from 1 to 2°C (Figure 8g), which is significant. Larger jumps, for example, from the preindustrial baseline period to 2°C and 3°C are also significant for both P (dry rootzone|high precipitation) (Figure 8g) and P (wet rootzone|high precipitation) (Figure 8h).

Surface and rootzone soil moisture event probability is also quite similar between the two regions in response to “normal” (central tercile) precipitation events (Figure S4 in Supporting Information S1): the probability of both dry surface and rootzone soil moisture months increase with warming, while the probability of a wet soil moisture month decreases. The interquartile range across models is larger and the significance in changes between warming levels is less robust in Western North America than the Mediterranean.

4. Discussion and Conclusion

The Mediterranean and Western North America are two regions where climate change is likely to drive significant increases in drought risk. Using a 19-member CMIP6 model ensemble, we find that low-precipitation anomalies will become much more effective at generating soil moisture droughts under various global warming levels, especially in the case of surface soil moisture. At the same time, high-precipitation anomalies in these same regions are likely to be much less effective at terminating droughts. At all degrees of warming, the multi-model

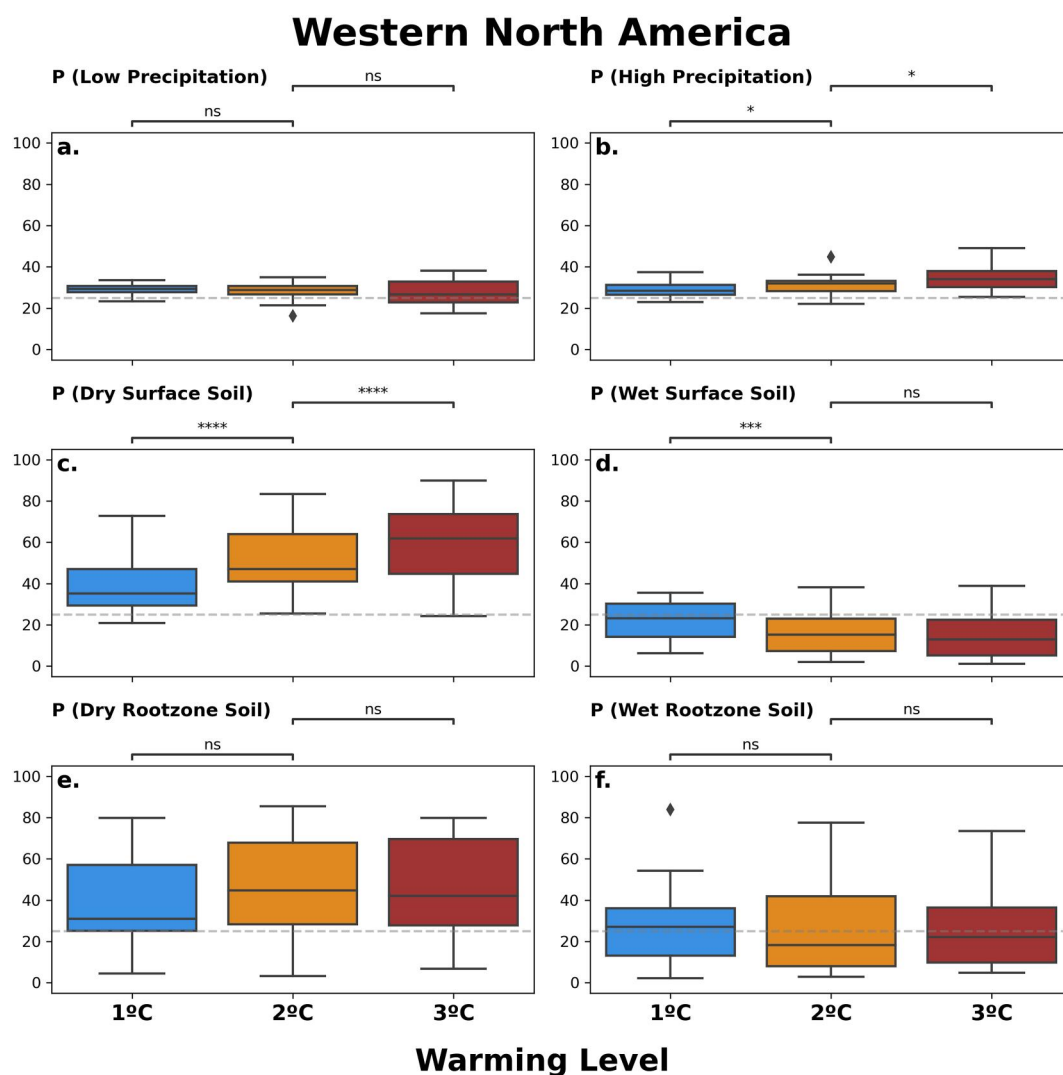


Figure 7. Precipitation, soil moisture, and warming relationships in Western North America. Likelihood of low or dry (25th percentile relative to preindustrial baseline) and high or wet (75th percentile) monthly standardized precipitation index (a, b), surface soil moisture (c, d) and rootzone soil moisture (e, f) anomalies, under three levels of warming in Western North America. Dotted line is the prescribed 25% probability during the pre-industrial baseline (1861–1880). Significance calculated using paired samples Wilcoxon tests (Charlier et al., 2022).

mean and median probability of a dry surface soil moisture anomaly increases in both the Mediterranean and Western North America, with the median probability increasing from the baseline to 2°C of warming by 182% (Mediterranean) and 88% (Western North America). The increased probability of dry soil surface moisture given a wet precipitation month is even larger at 6 and 3 times more likely for the Mediterranean and Western North America, respectively. Conversely, the median probability of an anomalously wet surface soil moisture, given a high-precipitation month, is 42% (Mediterranean) and 26% (Western North America) less likely at 2°C than during the baseline period. The probability of a wet rootzone soil moisture during a high-precipitation period in the Mediterranean is down by 87% at 2°C and in Western North America, the probability decreases by 32%, relative to baseline.

Both regions experience drier soils (Figures 1 and 5) and increased drought risk (Figures 3 and 7) with warming, but with some notable differences. Overall drying is more severe in the Mediterranean, caused by declining precipitation and increased evapotranspiration in all months and seasons. As a result, drought risk and the probability of dry soils during low and high precipitation periods increases sharply for both surface and rootzone soil moisture. By contrast, annual precipitation actually increases in Western North America, and the soil

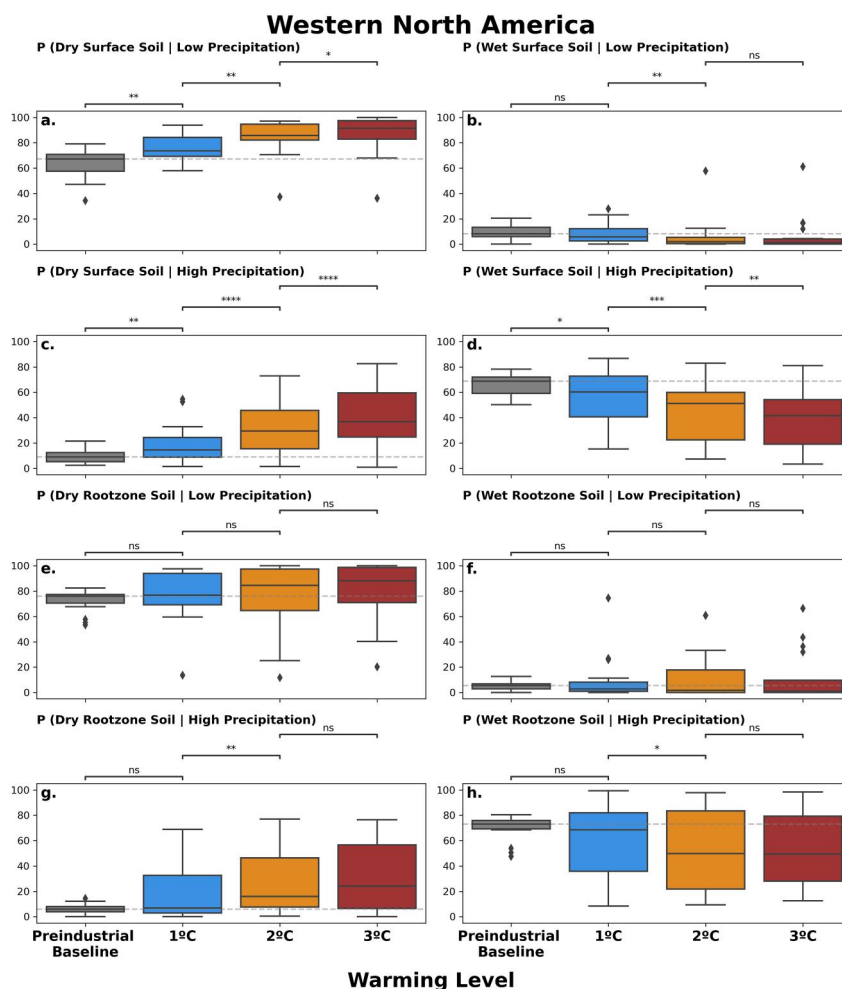


Figure 8. Conditional relationships between precipitation, soil moisture and warming in Western North America. Conditional probability of a dry (25th percentile relative to preindustrial baseline) or wet (75th percentile) surface soil (a–d) or rootzone soil (e–h) moisture anomaly given a low (25th percentile: a, b, e, f) or high (75th percentile: c, d, g, h) standardized precipitation index. Significance calculated using paired samples Wilcoxon tests (Charlier et al., 2022).

moisture drying tendency is largely through increased evaporative losses, resulting in less severe drying compared to the Mediterranean. As a consequence, the largest and most significant changes in soil moisture and precipitation relationships occur for the surface soil moisture.

This research highlights plentiful avenues for future research, particularly in the influences of regional seasonality and model differences on the varying responses to precipitation between surface and rootzone soil moisture. While surface soil moisture responses to warming were similar in both regions, rootzone soil moisture drying in the Mediterranean is strong and more significant. This may be due to the longer seasonal-to-yearly memory of a deeper soil column. Due to the overall increasing moisture budget in Western North America, rootzone soil moisture levels are largely independent of short-term or even seasonal changes in evaporative demand and precipitation in comparison to the Mediterranean. We might also expect to see differences in how other drought metrics, such as streamflow, reservoir storage, and groundwater recharge, might respond. In using the IPCC AR6 regional definitions for the Mediterranean and Western North America, we also average over a variety of different biomes and geographies; this analysis is not granular enough to determine the future drought risk of specific subregions or catchments and therefore is limited in real-world applicability. A robust seasonal analysis may also be necessary to determine the impacts of drought risk for agricultural impact, however replicating the analysis for the warm seasons (April–September) over Western North America yielded similar results to those described in this paper.

In our analyses, some models fall outside the interquartile range (represented as diamonds in Figures 3, 4, 7, and 8), however there is no evidence that these outliers are due to poor precipitation or soil moisture climatology. For example, in the Mediterranean, GISS-E2-1-G falls outside the interquartile range of probabilities in both the dry and wet surface soil moisture at all warming levels (Figures 3c and 3d), without having substantially different precipitation or soil moisture climatology from the other models in the ensemble in either region (Figures S5–S10 in Supporting Information S1). In the conditional probability analyses (Figures 4 and 8), no single model is consistently an outlier with most of the members of our multi-model ensemble falling outside the interquartile range at least once. Future research could investigate model disagreements to better understand these divergences.

This analysis focuses on monthly precipitation and soil moisture anomalies and does not consider other precipitation characteristics that are also expected to change with warming. It is well understood, for example, that increasing global average temperatures are leading to increases in precipitation extremes that are much more robust and unidirectional than changes in mean precipitation in all regions, including the Mediterranean and Western North America (Seneviratne et al., 2021). Even in the absence of overall changes to monthly mean rainfall, these changes in precipitation extremes and the temporal distribution of precipitation (e.g., frequency of events within a month) can have significant, and often different, impacts on soil moisture and runoff (Mimeau et al., 2021; Scott et al., 2017) by making droughts more likely and simultaneously more difficult to terminate. Future analyses should investigate the impact of individual extreme precipitation events on drought response and recovery.

Most droughts are terminated by high precipitation, but the heavy rainfall often associated with these events can also cause flooding, erosion, and landslides. Our results show that in a warmer world, these equivalent precipitation anomalies are less effective at ending droughts, but their influence on the other extremes is less certain. Our results also suggest that drought terminations themselves will require even more precipitation, highlighting potentially even larger extreme precipitation and flood risks and further compounding impacts on people, ecosystems, and water management systems (Bezerra et al., 2019; Pendergrass et al., 2017; Savelli et al., 2021; Swain et al., 2018; Zscheischler et al., 2020). In a warmer world, the drought-ending benefits of the precipitation may therefore be outweighed by negative physical and social impacts of an event large enough to terminate the drought. Water management and policy will therefore need to adapt to this shifting relationship between precipitation and soil moisture to help reduce the impacts of both dry and wet hydroclimate extremes. However, our work demonstrates that these shifts scale with the magnitude of warming, highlighting the potential benefits of climate mitigation for reducing impacts and facilitating adaptation.

Data Availability Statement

The World Climate Research Programme (WCRP, 2022) coordinates and promotes CMIP6 and the complete archive of CMIP6 output is freely available for download from the Earth System Grid Federation (ESGF) at <https://aims2.llnl.gov/search/cmip6/>. For individual model citations, see Table 1.

Acknowledgments

B.I.C., J.E.S., and K.M. are supported by the Department of Energy (DOE) award ESC0022302. J.E.S. is additionally supported by NSF award AGS 2101214 and by NOAA MAPP award NA200AR4310425. M.T. is supported by NSF award AGS-1934358 and NOAA award NA200AR4310379.

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