Historical and Projected Future Drought in Oregon

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We explored historical drought occurrences in Oregon on the basis of common meteorological and hydrological drought indices. We also investigated projections of future drought in Oregon on the basis of downscaled climate model simulations for the twenty-first century.

Background

Definitions of drought

Drought refers to conditions in which water supply is insufficient to meet demand (Redmond, 2002; Swann, 2018). The many conceptual and mathematical definitions of drought vary among locations and applications (Wilhite and Glantz, 1985; Rasmussen et al., 1993). For example, meteorological and hydrological drought are driven by physical factors and do not describe the effects of drought on humans or ecosystems. **Meteorological drought** traditionally has been defined by lack of precipitation, but is better defined as evaporative demand that exceeds precipitation over a prolonged period. **Hydrological drought** occurs when extended periods of meteorological drought affect surface or subsurface water supply, and is most consequential for society when water supply does not meet human demand. Several other types of drought are defined on the basis of their effects on particular components of human and natural systems. For example, **agricultural drought** occurs when lack of surface or subsurface water supply adversely affects agricultural production.

Drought Classification

The weekly U.S. Drought Monitor, a commonly used drought classification system, is based entirely on assessment of physical indicators of drought and the duration of dry conditions. The U.S. Drought Monitor's drought classes reflect assessment of physical indicators of drought severity and spatial extent, most of which are meteorological or hydrological (e.g., precipitation, snow water equivalent [SWE], streamflow, soil moisture, shallow groundwater, and evapotranspiration), at several temporal extents (Svoboda et al., 2002). The weekly national map of drought severity differentiates short-term drought (duration less than six months) from long-term drought (duration greater than six months). The U.S. Drought Monitor is used to inform consideration of administrative drought declarations, such as emergency drought declarations issued at the county level by the Governor of Oregon or drought declarations issued by the U.S. Department of Agriculture (USDA) to trigger financial relief and crop insurance programs for agricultural producers. Administrative drought declarations are based not only on physical indicators of drought but on the impacts of drought. These impacts may include shortages of water for municipal use, irrigation, livestock rearing, and other social and economic priorities.

Drought in Oregon

West of the Cascade Range, the annual climate of Oregon is characterized by a well-defined winter wet season and summer dry season. The climate east of the Cascade Range is drier than that west of the Cascade Range, and precipitation tends to peak in late spring and early summer. Western Oregon is prone to seasonal drought due to low precipitation during winter, such as occurred during the historic drought of 1976–1977. Flash droughts also occasionally occur throughout Oregon (Otkin et al., 2018; Pendergrass et al., 2020). Flash droughts are characterized by rapid-onset periods of elevated surface temperatures, low relative humidities, precipitation deficits, and a rapid decline in soil moisture. These conditions often occur in Oregon during late spring and summer heat waves, and the impacts of flash drought can emerge in as little as a week (Mo and Lettenmaier, 2015; Rupp et al., 2017). One week also tends to be the shortest duration of conditions that are characterized as flash drought.

A megadrought that is estimated to be one of the most severe since at least 800 CE is affecting most of the southwestern United States, extending north to southern and eastern Oregon (Williams et al., 2020, 2022). Megadrought generally refers to a drought that persists for longer than a decade, although isolated wet years can occur during a megadrought. Additionally, as of late November 2023, much of Oregon is either in or recovering from a multiple-year drought that began in water year 2020 (Bumbaco et al., 2021, 2022, 2023). Multiple-year droughts are those that persist for more than one water year (October 1 – September 30). Impacts on human and natural systems can become more severe in each consecutive year of drought as groundwater, soils, and surface-water bodies continually dry without normal recharge.

Quantitative Metrics of Drought

Diverse metrics or indices are used to quantify the duration and intensity of drought. Most are based on standard meteorological observations, mainly precipitation and temperature, or an estimate of evaporation from the land surface. Streamflow observations also are used to assess drought at the watershed level. Drought indices based on meteorological observations attempt to represent simplified balances between precipitation and evaporation and evapotranspiration. In this summary, we consider two common drought indices, the Standardized Precipitation Index (SPI) and the Standardized Precipitation-Evapotranspiration Index (SPEI). We consider a third index, the Standardized Streamflow Index (SSI), in the Appendix. Standardized drought indices allow for comparisons among regions and seasons. These drought indices are used operationally for drought severity classification by the U.S. Drought Monitor and in research on historical and projected drought occurrence.

Standardized Precipitation Index (SPI)

The Standardized Precipitation Index (SPI) is skillful in drought determination, easily understood, and effectively characterizes the frequency and intensity of drought caused by lack of precipitation. The index was designed to quantify precipitation deficits and surpluses over multiple temporal extents with different climate conditions (McKee et al., 1993; Edwards and

McKee, 1997), and skillfully determines drought in northwest Oregon (Keyantash and Dracup, 2002). Values of the SPI are based on long-term precipitation records at temporal resolutions of months or longer, but can be adapted to any temporal resolution. Estimates of statewide precipitation and SPI from 1950–2022 were highly correlated, suggesting that drought indices derived from either source will be quite similar (Appendix).

The SPI does not account for variation in evaporative losses or runoff, and therefore does not adequately account for the supply and demand concept of surface water availability. Water loss from evaporation or evapotranspiration can strongly affect surface water availability. Neglecting these losses can lead to miscategorization of drought conditions, particularly in climates with well-defined wet and dry seasons, such as those in Oregon. The Standardized Precipitation-Evapotranspiration Index (SPEI; Vicente-Serrano et al., 2010) improves on the SPI by incorporating estimates of evaporative loss. Uncertainty in values of the SPI increase during the dry season in arid climates (Wu et al., 2007). There are few such cases in Oregon at seasonal and longer extents.

Standardized Precipitation-Evapotranspiration Index (SPEI)

The dimensionless Standardized Precipitation-Evapotranspiration Index (SPEI) is a primary metric used operationally to assess the existence and severity of meteorological and hydrological drought, especially in the western United States (Vicente-Serrano et al., 2010). The SPEI compares the net water balance between precipitation and potential evapotranspiration (evapotranspiration from a large area with uniform vegetation and unlimited soil water) between a recent period of time and a historical period (Vicente-Serrano et al., 2010). The SPEI allows for evaluation of drought severity in different locations and time periods, identification of different drought types (Ahmadalipour et al., 2017), and consideration of the role of temperature-driven evapotranspiration in drought. SPEI is a reliable predictor of annual streamflow in the Pacific Northwest (Abatzoglou et al., 2014; Peña-Gallardo et al., 2019) and water levels in lakes and reservoirs (McEvoy et al., 2012). Accordingly, the SPEI at extents from 3 to 24 months is a key indicator of drought severity and extent in the U.S. Drought Monitor for Oregon.

Relation between indices of meteorological drought and streamflow

Our analysis suggested that both the SPI and SPEI, when computed over the water year, are reasonable proxies for seasonal to annual streamflow variability, and therefore are reasonable metrics of hydrological drought (Appendix). The same analysis indicated that the SPI is a more reliable proxy for interannual variability in streamflow in watersheds west of the Cascade crest than in watersheds east of the Cascade crest.

Data Selection and Use

Data selection affects how different indices represent drought severity and extent. Among the considerations in selecting data are the need for long-duration historical records, the available variables, and the spatial and temporal resolutions of the data. Given these considerations, we used PRISM monthly gridded precipitation and temperature data in our analyses of historical drought. The PRISM (Parameter-elevation Regressions on Independent Slopes Model) Climate Mapping Program is an ongoing effort to produce and disseminate detailed, high-quality, spatially explicit climate data (Daly et al., 1994). The PRISM data are based on observations over a long period of time. Measurement errors and data gaps resulting from variation in the spatial and temporal density of historical observations can affect the quality of analyses that are based on PRISM data. Nevertheless, the PRISM data are among the best estimates of precipitation and temperature in the highly variable terrain of the western United States. PRISM data are a key component of operational drought monitoring in Oregon. The PRISM climate analysis is updated regularly as more observations become available. PRISM temperature and precipitation fields are provisional for 6 months and significant changes can be expected for up to 2 years. Therefore, in this report, drought indices derived from PRISM data since November 2021 should be considered preliminary.

We based the projections of future climate in our analyses on output from an ensemble of regional climate model simulations conducted by the North American Coordinated Regional Downscaling Experiment (NA-CORDEX; Mearns et al., 2016). The boundary conditions of the regional climate models were derived from diverse coupled global climate model simulations that assumed a continuation of current levels of greenhouse gas emissions through the year 2100 (RCP 8.5).

Oregon’s Drought History

We provide two perspectives on Oregon's drought history. The first, a statewide characterization, is perhaps the simplest summary of drought conditions across the state. This summary is incomplete because historical drought conditions varied substantially across the state, particularly east and west of the Cascade Range. To account for this gradient, we also characterized historical drought in six regions within Oregon. We provide a drought history for each of Oregon’s 36 counties in the Appendix.

During 18 of the last 24 water years, Oregon’s annual water year precipitation was below the average from 1901–2000 (Figure 1). As measured by total statewide precipitation, water years 2001 and 2020 ranked as the third and fifth driest on record. Since 1896, the five water years with the lowest precipitation statewide were 1977, 1924, 2001, 1994, and 2020. The average temperature in Oregon also was warmer than normal during 21 of the last 24 water years (Figure 2), which contributed to higher rates of evapotranspiration and more frequent drought.

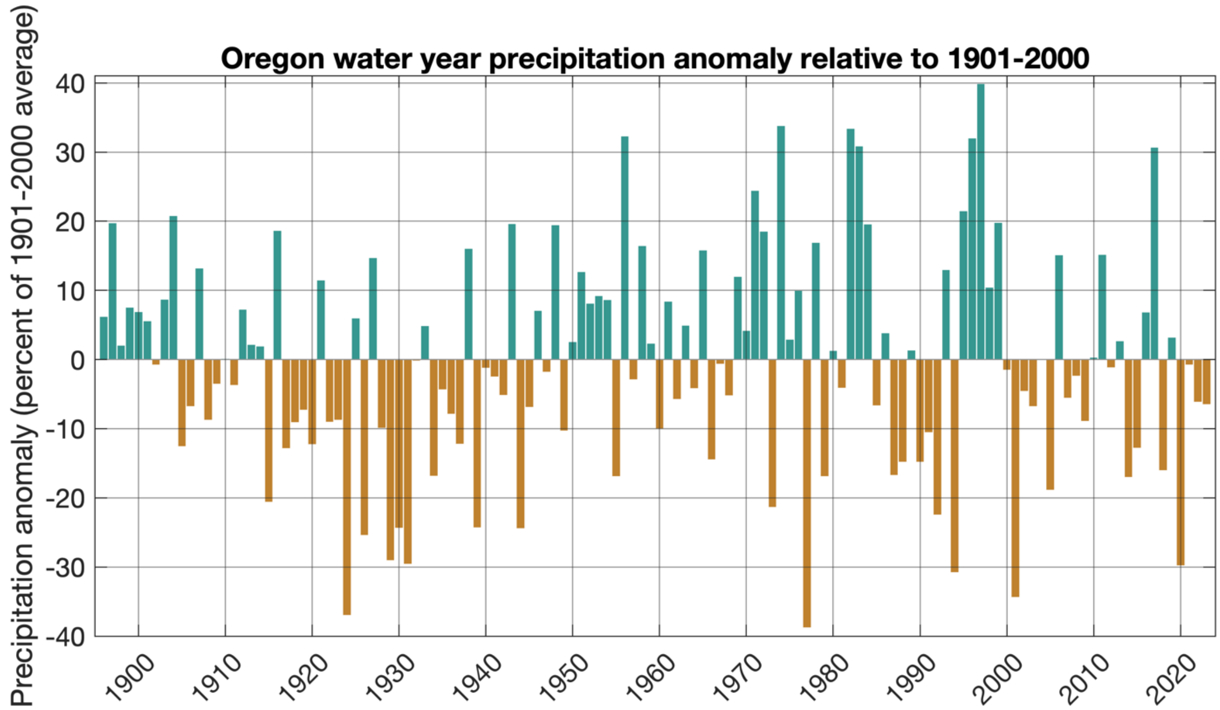


Figure 1. Total precipitation for the water years of 1896–2023 as a percentage of the 1901–2000 statewide average of 35.32”. Data from the PRISM Climate Group.

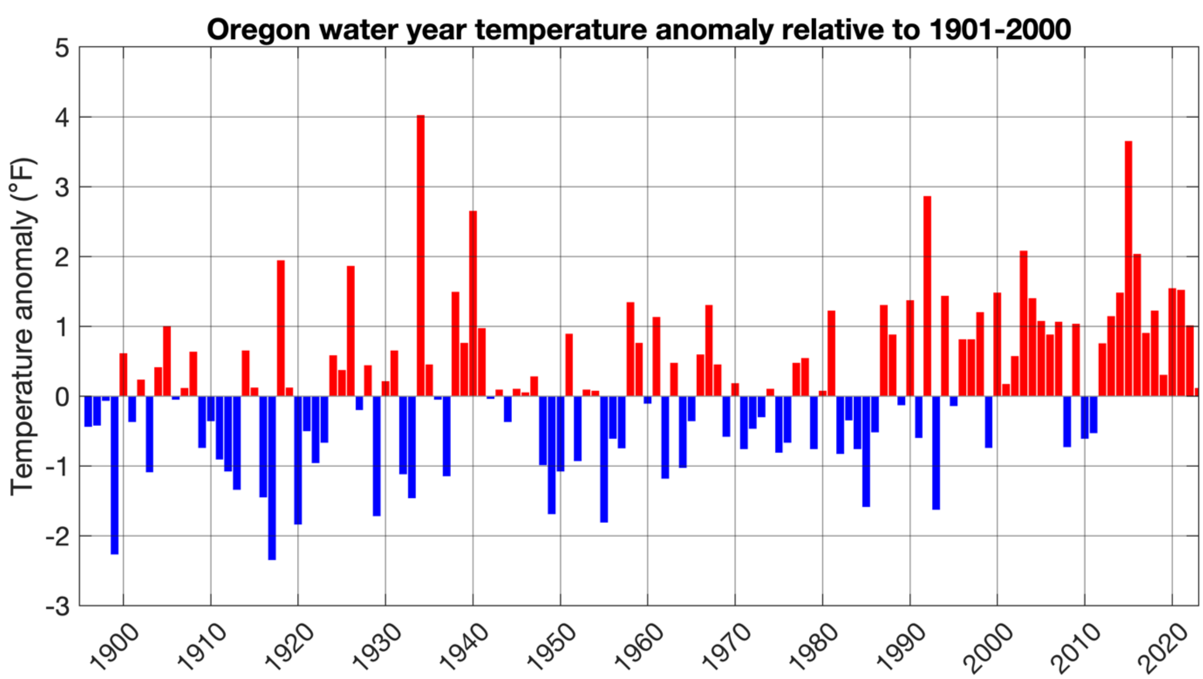


Figure 2. Temperature anomalies in Oregon during water years 1896–2023 relative to the average temperature from 1901–2000. Data from the PRISM Climate Group.

The single water year with the lowest precipitation was 1977, following a historically dry autumn and winter (Dickson, 1977). Precipitation was highest during water year 1998. Multiple moderately to extremely wet years during the early 1980s and late 1990s were at least partially associated with years with an El Niño classified as Very Strong, the strongest class.

Given the correlation between drought and streamflow (Appendix), we summarized statewide and county-level drought on the basis of SPI and SPEI. Correlations between drought and streamflow indices in some watersheds were slightly higher over shorter periods of time, but use of a metric that encompassed the water year retained major drought periods while simplifying presentation. We selected 12-month periods to coincide with water years represented in the monthly PRISM data (1896–2022).

Statewide Drought History

Both the SPI and the SPEI indicated that the five water years in which extreme or exceptional drought occurred in Oregon were 1924, 1977, 1931, 1994, and 2020 (Figure 3). The two indices identified three periods of persistent multi-year drought in Oregon: 1924–1938, 1987–1993, and 2000–2022. The 1977 drought, the most exceptional single-year drought in Oregon's recorded history according to most metrics, was preceded by three water years that were wetter than normal (1974–1976) and followed by a moderately wet water year (1978). Since 1950, two multi-year wet periods are clear from SPI and SPEI: 1982–1984 and 1995–1999. Both occurred in association with a Very Strong El Niño (1982–1983 and 1997–1998). Average precipitation across the state during the only other Very Strong El Niño (2015–2016) was slightly higher than normal (Figure 1), and SPI for water year 2016 was in the normal range (Figure 4).

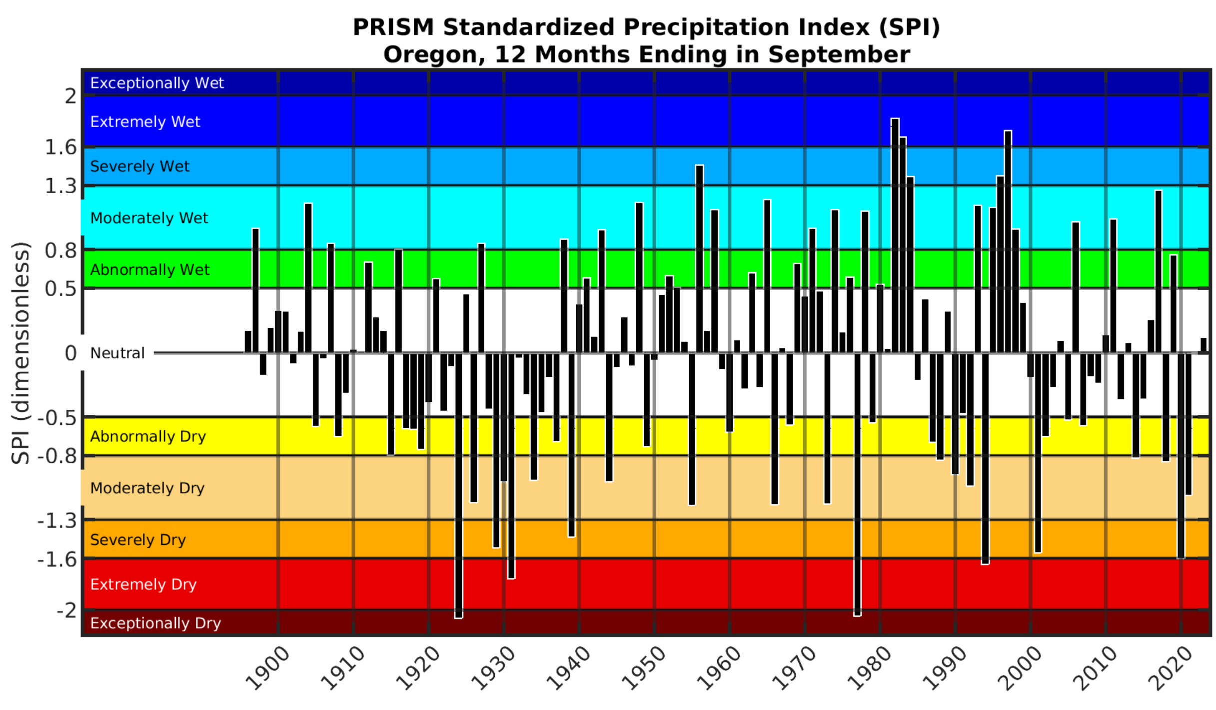


Figure 3. Drought classification in Oregon based on the SPI, derived from PRISM data, for each water year from 1896–2023. Drought classification based on the water year SPEI yielded similar results, as did analysis of ERA5-Land data (Appendix). The background colors in the SPI time series correspond to dry conditions as represented by the U.S. Drought Monitor and wet conditions as represented by the Climate Toolbox's U.S. Water Watcher tool (climatetoolbox.org/tool/Historical-Water-Watcher).

Because the SPI and SPEI account for spatial and temporal variation in precipitation and their relation to historical climate, the most severe drought years identified by these indices are not necessarily the years with the lowest average precipitation. January precipitation that is one inch below normal, for example, has a different effect near coastal Newport than inland near Bend or Burns. Furthermore, when one relies on a statewide estimate of precipitation, precipitation surpluses in one region of the state may be masked by precipitation deficits in other regions, such as occurred during the 2016 water year. The statewide SPI and SPEI values account for such variation in precipitation and yield a more robust estimate of the location and timing of drought conditions than would precipitation alone.

Regional Drought History

The statewide drought history is a useful summary, but may not accurately reflect regional conditions. Oregon is a large state with diverse climate regions and water sources, and environmental conditions can vary substantially from north to south or on either side of the Cascade Range, leading to significant variability in drought status. We accounted for regional variability in drought history by classifying drought within six regions of Oregon: Northwest, Southwest, Northcentral, Southcentral, Northeast, and Northwest (Figure 4). The climate within each region tends to be similar over time. We based our assessment on SPI and SPEI derived from PRISM and ERA5-Land at the county level since water year 1950. We also conducted a detailed sensitivity analysis of how use of different metrics and temporal extents affected drought classifications for each region (Appendix). In most cases, both metrics identified drought during the same years.

In addition to a time series of the drought classification based on the water year SPI (SPI12) (Figure 5), we provide a time series of the drought classification based on the 3-month SPI (SPI3). The latter provides context about when drought conditions developed. Furthermore, we compared the drought classifications that were based on SPI and SPEI for each region and season (Figure 6). This comparison suggests whether a drought was driven by lack of precipitation or by excessive evapotranspiration.

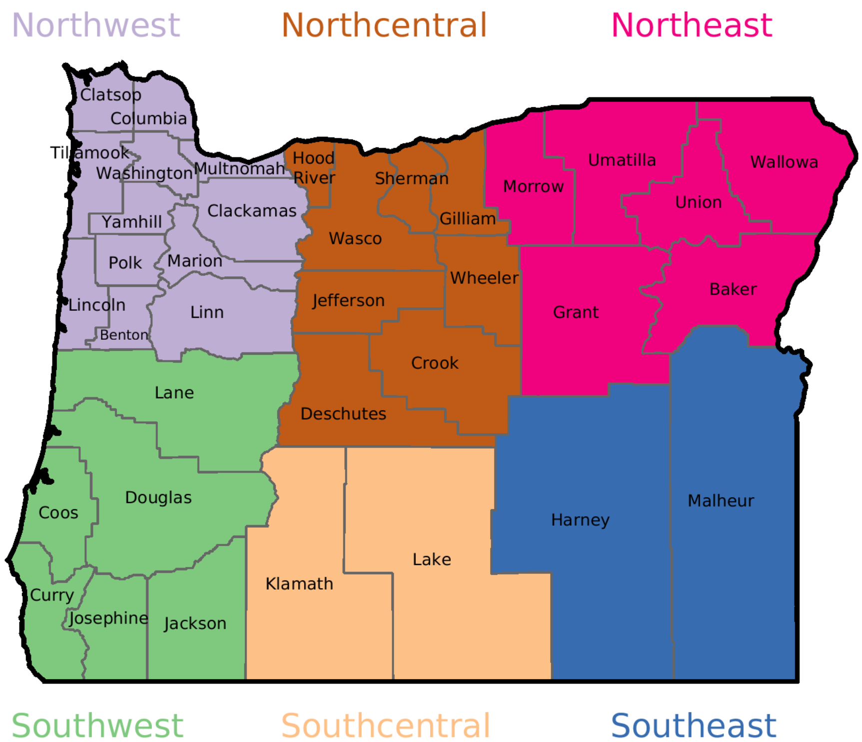


Figure 4. Oregon's thirty-six counties grouped into six regions on the basis of drought conditions.

The summer (June-July-August) SPEI consistently indicated more intense, persistent, and widespread drought since 2015 than the SPI. The spring (March-April-May) SPI indicated far more severe drought conditions during water year 2021 than the SPEI (Figure 6) due to lack of precipitation and cooler than normal temperatures (Bumbaco et al., 2022). The SPEI indicated uniform D4 conditions, or drought that was 2-3 categories more intense than indicated by the SPI, during summer 2022.

Northwest region
All metrics identified drought in Northwest Oregon during the water years of 1973 (~D1), 1977 (D3-D4), 1979 (~D2), 1993 (~D2), 1994 (D2-D3), 2001 (D3-D4), 2005 (~D3), 2009 (~D1), 2014–2015 (~D1), and 2019–2021 (D1-D3) (Figures 5, 6).

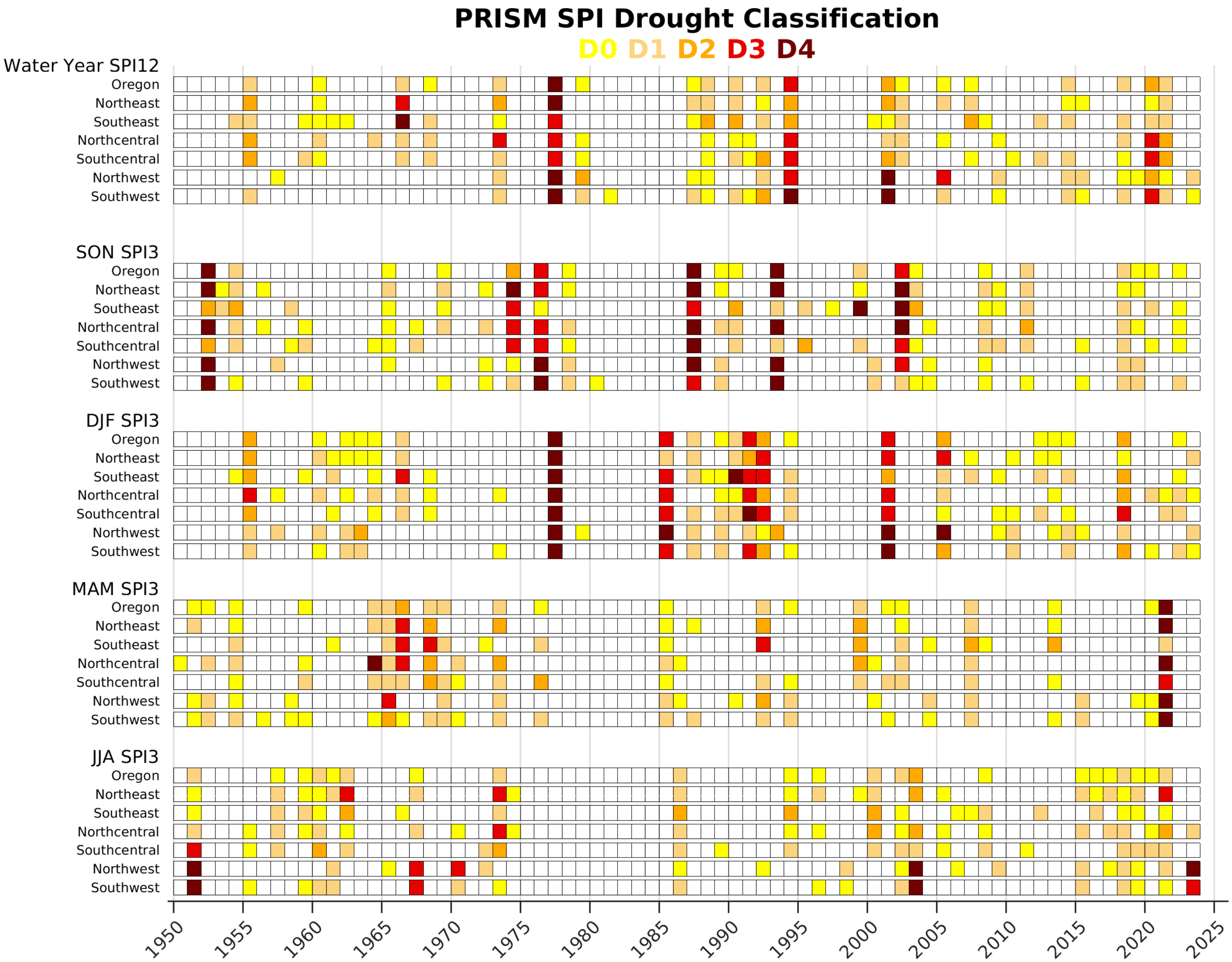
Northcentral region
All metrics identified droughts in Northcentral Oregon during the water years of 1955 (~D2), 1960 (~D1), 1963 (D1-D3), 1965 (~D1), 1967 (~D1), 1973 (D2-D3), 1977 (D2-D4), 1994 (D1-D4), 2001–2002 (~D1-D3), 2004 (D1-D4), 2018 (~D1), and 2020–2021 (~D2-D3). Drought classifications in Hood River County were distinct from those in other counties in the region (Appendix).

Northeast region
All metrics identified droughts in Northeast Oregon during the water years of 1955 (~D2), 1965 (D2-D4), 1973 (D1-D3), 1977 (D3-D4), 1987-1988 (D1-D2), 1990 (~D1), 1992 (D1-D3), 1994 (D1-D3), 2001 (D1-D3), 2004 (D1-D3), 2006 (~D1), and 2020–2021 (~D1). Drought in Morrow County, especially as identified by PRISM, tended to be more intense than in surrounding counties during the last decade (Appendix). The apparent difference in county-level drought intensity may reflect low density of observation stations.

Southwest region
All metrics identified droughts in Southwest Oregon during the water years of 1955, 1973, 1977 (D4), 1979 (D1), 1986 (D1), 1990 (~D1), 1992 (~D1), 1994 (D3-D4), 2001 (D4), 2014 (D1-D3), 2018 (D1), 2020 (~D3), and 2021 (~D1).

Southcentral region
All metrics identified droughts in Southwest Oregon during the water years of 1955 (D2-D3), 1959 (D1), 1967 (D1), 1977 (D2-D3), 1992 (D1-D2), 1994 (D2-D3), 2001 (D1-D3), 2020 (D3), and 2021 (D2-D3).

Southeast region
All metrics identified droughts in Southwest Oregon during the water years of 1954-1955 (D1), 1965 (D3-D4), 1977(D3), 1988 (D1-D2), 1990 (~D2), 1992 (D1), 1994 (D2), 2002 (D2), 2006 (D2), 2012 (D1-D2), 2014 (D1), 2018 (D1), and 2020–2021 (D1-D2). The ERA5-Land estimate of the intensity of the 2020–2021 drought was one or two classes more intense than that of the PRISM estimate (Appendix).



PRISM SPI Drought Classification
D0 D1 D2 D3 D4
Water Year SPI12
Oregon
Northeast
Southeast
Northcentral
Southcentral
Northwest
Southwest
SON SPI3
DJF SPI3
MAM SPI3
JJA SPI3
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025

Figure 5. State and regional drought classifications based on the PRISM-derived SPI for each water year and season since 1950. Colors correspond to the USDM drought categories D0-D4 (see legend below title). Squares without color indicate either neutral or wet meteorological conditions. Water years are defined as the 12-month period from October–September for the year including September. For example, water year 2022 includes October 2021 through September 2022. The 3-month seasonal averages include the months of December-January-February (DJF), March-April-May (MAM), June-July-August (JJA), and September-October-November (SON). The seasonal averages also correspond to the year in which the season ends. For instance, the DJF SPI and SPEI for 1951 include December 1950, January 1951, and February 1951.

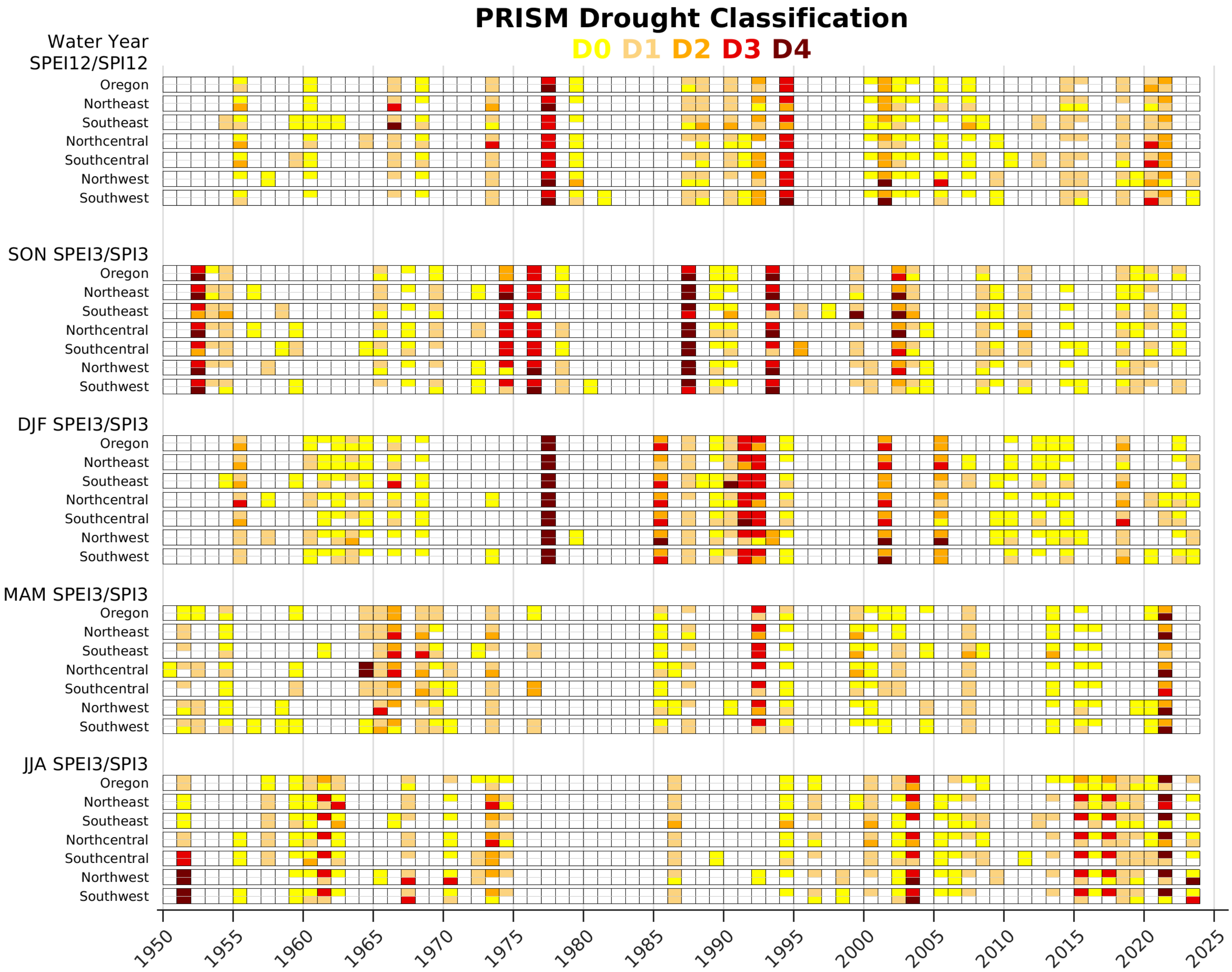

PRISM Drought Classification
D0 D1 D2 D3 D4
Water Year SPEI12/SPI12
SON SPEI3/SPI3
DJF SPEI3/SPI3
MAM SPEI3/SPI3
JJA SPEI3/SPI3
Oregon
Northeast
Southeast
Northcentral
Southcentral
Northwest
Southwest
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025

Figure 6. As for Figure 5, except split tiles represent drought classifications based on the SPEI (top) and SPI (bottom).

Projections of Future Drought

Projections of future drought typically are based on one of two types of analysis (Hrachowitz et al., 2017). The first directly simulates changes in streamflow and soil moisture on the basis of Earth System Models forced with projected emissions of greenhouse gases. Earth System Models include atmospheric and ocean models that are similar to those in traditional climate models. They also incorporate an interactive land-surface model that allows vegetation, surface albedo, and soil moisture to respond dynamically to changes in climate and emissions of greenhouse gases. Earth System Model simulations generally project that during the twenty-first century, streamflow and root-zone soil moisture in Oregon will decrease in summer, increase in winter, and have a similar annual mean (Lai et al., 2023; Zhou et al., 2023). However, the ~100-km horizontal resolution of most Earth System Model simulations is too coarse to resolve the coastal and orographic effects that modulate Oregon's climate and hydrology.

An alternative method of projecting drought is to calculate the indices used to assess historical drought conditions, but with meteorological variables derived from climate model simulations rather than historical observations or reanalysis. Such an analysis does not require an interactive land-surface model, and therefore can be performed with output from any standard climate model. However, there are two major caveats to this second method.

First, most global climate models have the same horizontal resolution as most Earth System Models, and as a result do not represent the Coast Range and Cascade Range. We attempted to mitigate this limitation by restricting our analysis to an ensemble of regional climate model simulations (NA-CORDEX) with horizontal resolutions of 25 km (Mearns et al., 2016). Although a resolution of 25 km cannot capture all changes in climate that correspond to changes in elevation in the Coast Range and Cascade Range, it is a substantial improvement over standard global models that do not represent the mountain ranges.

Second, indices that incorporate potential evapotranspiration (evapotranspiration from a large area with uniform vegetation and unlimited soil water) exaggerate the increase in aridification and drought risk as climate changes if they do not account for changes in water use by plants as atmospheric concentrations of carbon dioxide change (Lemordant et al., 2017; Yang et al., 2018; Scheff et al., 2022). We calculated potential evapotranspiration with three different equations to evaluate the sensitivity of the SPEI, and therefore the drought classification, to the method used to estimate water use by plants. The first, the Thornthwaite equation (Thornthwaite, 1948), emphasizes near-surface air temperature anomalies. This equation effectively estimates potential evapotranspiration in the historical data record, but tends to overestimate the probability of future drought when projected future air temperatures exceed the historical values used to calibrate the model (Vicente-Serrano et al., 2009; Hoerling et al., 2011). The second and third equations, variations of the Penman-Monteith equation, depend not only on near-surface air temperature but on relative humidity, wind speed, net surface radiation, and surface vegetation. The second equation (FAO-56 Penman-Monteith) derives potential evapotranspiration from a hypothetical grass surface that is 0.12 m (~4.7 inches) thick

(Allen et al., 1998). The third equation (CO_2-aware Penman-Monteith) accounts for reduced transpiration by plants as CO_2 concentrations increase (Yang et al., 2018; Scheff et al., 2022).

At regional extents, the magnitude and sign of the projected future trends in drought varied substantially (Figure 7). Most increases in precipitation were projected to occur east of the Cascade Range, with average trends exceeding 0.3 inches per decade. The positive trends were statistically significant west of the Cascade Range in the Rogue Valley and northern Willamette Valley. By contrast, precipitation was projected to decrease along much of the west slopes of the Cascade and Coast Ranges, but the changes were statistically significant only in the southwestern corner of the state (Curry County) and in parts of eastern Linn and Marion Counties near Detroit Lake. Regional trends in potential evapotranspiration were less variable, with statistically significant increases projected across the state.

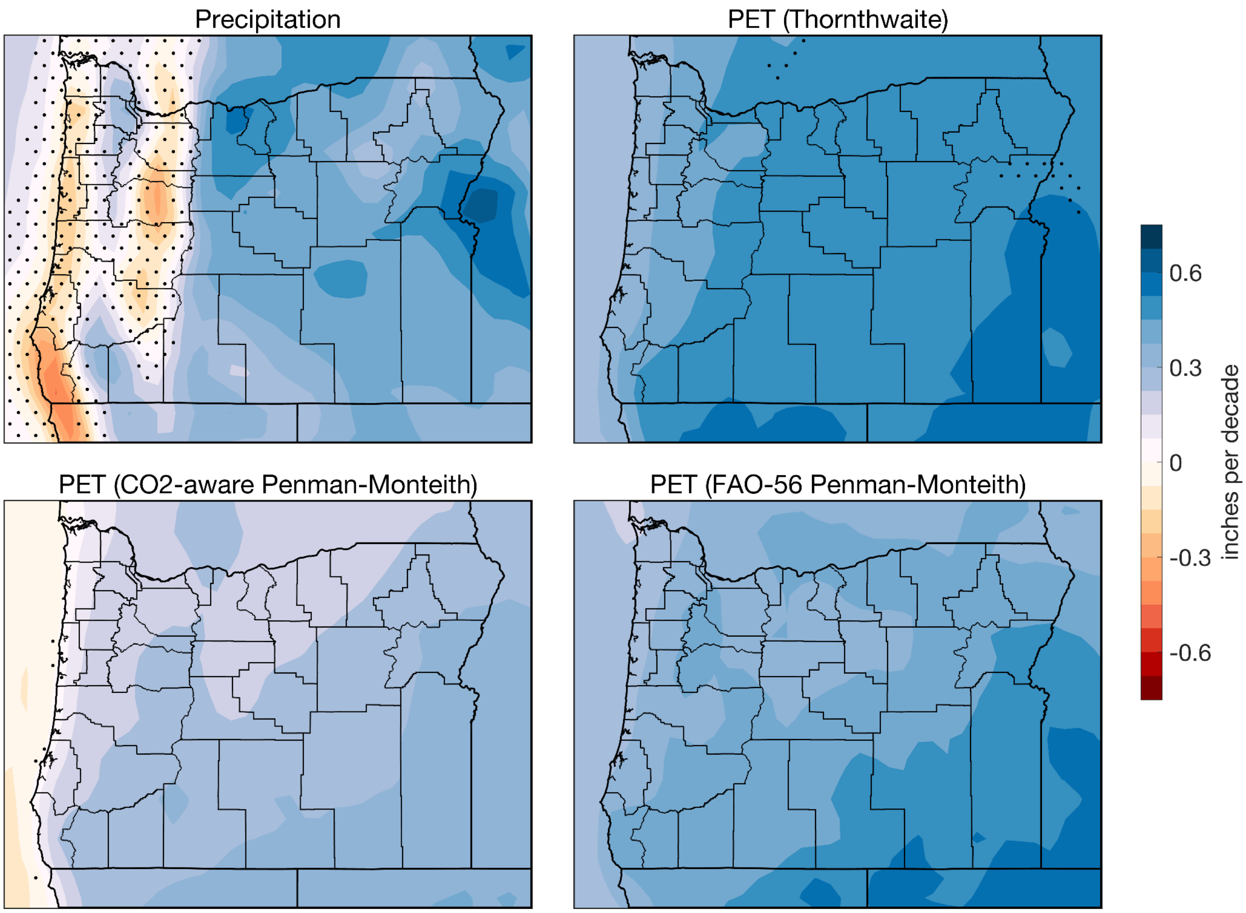


Figure 7. Linear trends in precipitation and potential evapotranspiration (PET) from 1950–2099 in the ensemble mean of the NA-CORDEX simulations. Stippling indicates that trends were not statistically significant at the 95% confidence level.

The spatial trends in precipitation (Figure 7) and SPI (Figure 8) were similar, albeit with somewhat different magnitudes. The spatial trends in precipitation and SPEI also were similar, but were offset by projected increases in potential evapotranspiration throughout the state. The

SPEI equations that did not account for future changes in plants' water use (Thornthwaite and FAO-56 Penman-Monteith) projected significant decreases in SPEI across most of the state, and therefore an increase in the incidence of drought. The more realistic equation that accounted for changes in water use by plants yielded a significant decrease in SPEI and a greater incidence of drought only along the western slopes of the Cascade and Coast Ranges; use of this equation led to a significant increase in SPEI and lower incidence of drought in the lower Deschutes basin of north-central Oregon.

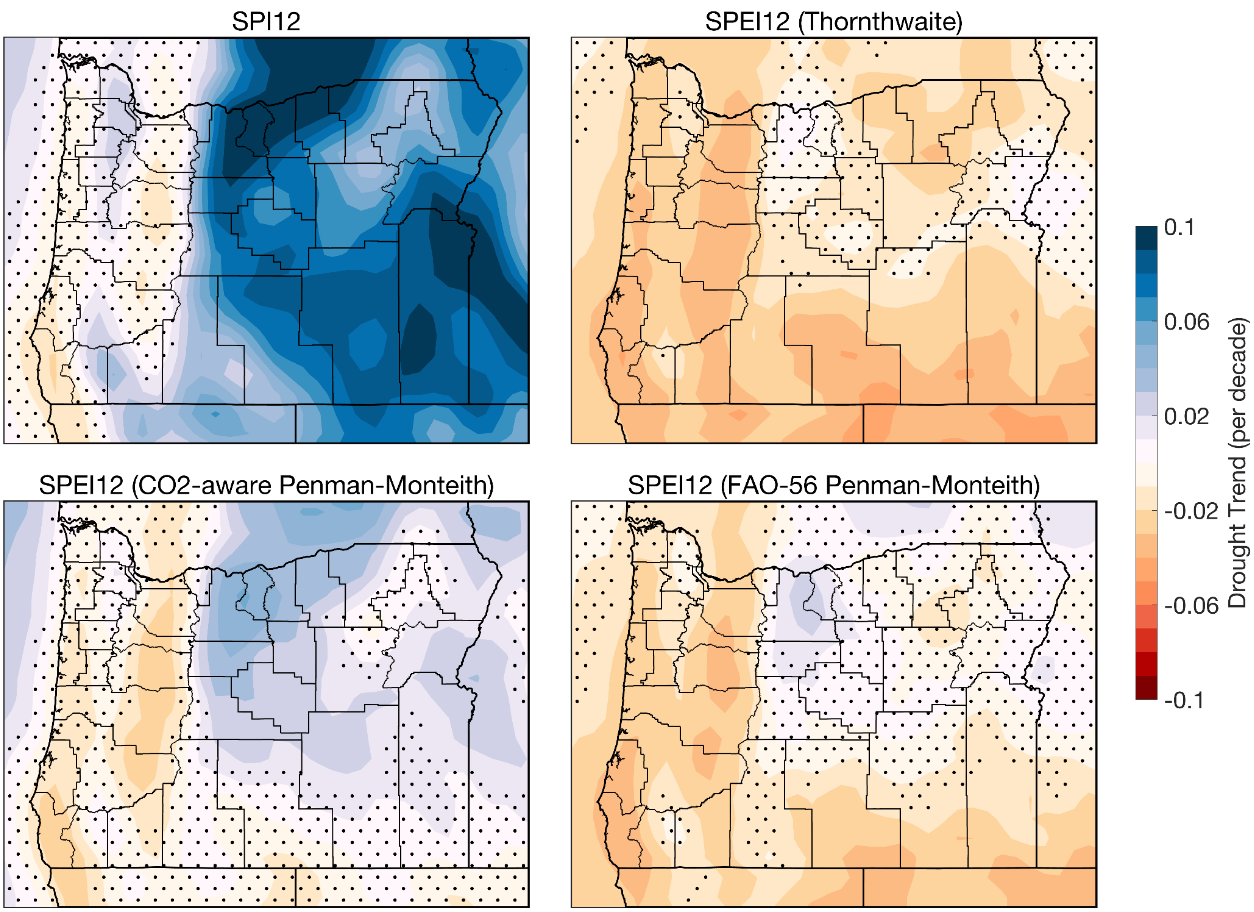


Figure 8. Linear trends in the 12-month Standardized Precipitation Index (SPI12) and Standardized Precipitation-Evapotranspiration Index (SPEI12) from 1950 through 2099 in the ensemble mean of the NA-CORDEX simulations. Stippling indicates that trends were not statistically significant at the 95% confidence level.

Even in regions where projected trends in the SPI12 and SPEI12 were positive, indicating wetter conditions, changes in the seasonal cycle of precipitation nonetheless may increase drought risk during part of the year. Across most of the state, precipitation likely will increase during winter and spring but decrease during summer. Increases in PET likely also will be greatest during summer, resulting in a significant decrease in the 3-month SPEI (SPEI3) during summer in all regions (Figure 9). This suggests a greater risk of drought during the summer growing season, when water demand is greatest.

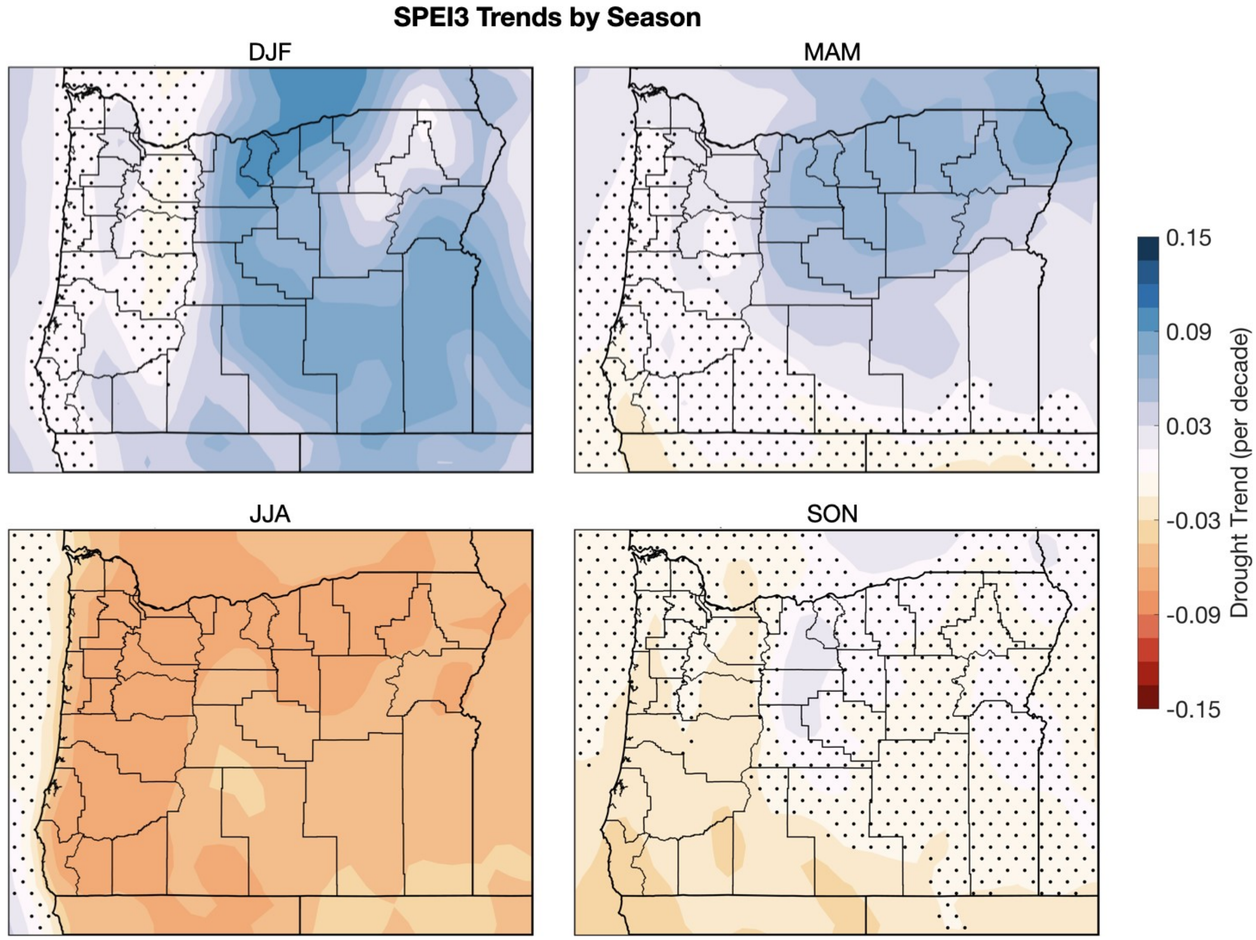


Figure 9. Linear trends in SPEI3 by season from 1950 through 2099 in the ensemble mean of the NA-CORDEX simulations. We calculated potential evapotranspiration (PET) with the CO_2-aware Penman-Monteith equation. Stippling indicates that trends were not statistically significant at the 95% confidence level.

Our analyses suggest that precipitation likely will increase across the state during the twenty-first century, especially east of the Cascade Range. Projected changes in precipitation in western Oregon are less certain. In contrast, our analyses suggests that potential evapotranspiration will increase across the state, with the effects of CO_2 on water use by plants only partially offsetting the increase in atmospheric dryness due to warmer temperatures. If we interpret SPEI as a proxy for soil moisture at the root zone of plants, then our results suggest that drought risk will increase during the twenty-first century on the west slopes of the Cascade Range and the southern Coast Range, decrease in the Deschutes and John Day basins in north-central Oregon, and change little elsewhere. However, due to a shift in the seasonal distribution of precipitation, drought risk during summer is likely to increase throughout Oregon.

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