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Key Points:

- Climate change adds conceptual and quantitative challenges to traditional drought assessments
- Reducing the sensitivity of drought indicators to non-stationarity is essential for accurately assessing future drought
- Multiple drought definitions or concepts are possible, and needed, to correctly assess drought in a changing climate

Supporting Information:

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

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Prioritization of Research on Drought Assessment in a Changing Climate

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Abstract Drought is a period of abnormally dry weather that leads to hydrological imbalance. Drought assessments determine the characteristics, severity, and impacts of a drought. Climate change adds conceptual and quantitative challenges to traditional drought assessments. This paper highlights the challenges of assessing drought in a climate made non-stationary by human activities or natural variability. To address these challenges, we then identify 10 key research priorities for advancing drought science and improving assessments in a changing climate. The priorities focus on improving drought indicators to account for non-stationarity, evaluating drought impacts and their trends, addressing regional differences in non-stationarity, determining the physical drivers of drought and how they are changing, capturing precipitation variability, and understanding the drivers of aridification. Ultimately, improved drought assessments will inform better risk management, adaptation strategies, and planning, especially in areas where climate change significantly alters drought dynamics. This perspective offers a path toward more accurate and effective drought management in a non-stationary climate system.

Plain Language Summary Drought is a period of abnormally dry weather that impacts water availability. Drought is commonly assessed to determine how abnormal it is, how severe its impacts are, or both. Climate change complicates traditional drought assessments. For example, some climates are becoming drier, making it more difficult to discern when a drought begins or ends. This paper highlights the challenges of assessing drought in a changing climate. It also identifies 10 key research priorities for advancing drought science and improving drought assessments in response to these challenges. These priorities include improving drought indicators to account for climate change; evaluating trends in drought impacts; acknowledging that the climate isn't changing in the same way or at the same rate everywhere, so drought assessments must address regional differences; determining how the underlying causes of drought are changing; exploring how changing precipitation characteristics, such as storm intensity and duration, impact drought; and better distinguishing drought in climates that are trending drier or wetter. We hope this

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work will improve drought assessments and will lead to better drought risk management, adaptation strategies, and planning.

1. Introduction

Drought is a period of abnormally dry weather of sufficient length to cause a serious hydrological imbalance (American Meteorological Society, 2019). Drought assessments generally aim to answer several questions: How abnormal is the dry weather? How serious are the impacts? What are its effects on water availability? Because drought is a relative phenomenon, a standard or reference for "normal" is needed to identify abnormally dry weather. Similarly, the severity of a drought is often couched in terms of past experience or expected impacts. Establishing the period and spatial extent that constitute normal in any given location is not straightforward. Changes in physical and human systems make establishing a normal for drought assessment more challenging.

Many climate indices use a 30-year baseline at the recommendation of the World Meteorological Organization (World Meteorological Organization, 2007, 2018). In contrast, many drought indices use a longer period of record to estimate the probability distribution of precipitation or other hydrologic quantities without considering changes in the probability distribution related to natural variability or human activities. As a result, the indices assume statistical stationarity within a non-stationary climate (Li et al., 2024; Lisonbee et al., 2024). Non-stationarity refers to temporal trends in the statistical properties of a time series, such as central tendency and variance (Figure 1). This is one of the motivations for this paper—where there is ample evidence for non-stationarity within the climate system (IPCC, 2023), the statistics used for drought planning often implicitly assume stationarity.

A strictly stationary time series is one in which the probability distribution of every possible sequence of values is equal to that of the time-shifted sequence (Salles et al., 2019). This definition is considered too strict for most applications. Therefore, most real-world examples provide a weakly stationary time series in which the mean and variance remain constant and the covariance structure depends only on the period (Salles et al., 2019; Yang & Zurbenko, 2010).

The complexities of non-stationarity in environmental data have been considered within the literature over the past century. For example, Köppen (1931) recognized quasi-periodic variations in the climate system and noted that there is no evidence of permanent change. Landsberg (1975) criticized the use of the term "normal" and the notion that climate is invariant even over several years. Landsberg (1975) further proposed terms to describe natural and human-caused climate variation over specific time scales. When multidecadal variability is large, the time series of drought indicators, such as streamflow, can have statistical properties indistinguishable from non-stationary time series, such as random walks (Figure 1). As with Köppen (1931) and Landsberg (1975), it is common to treat such variability as equivalent to non-stationarity although the underlying processes may be stationary. The statistics of successive 30-year segments can be vastly different even in the absence of a long-term trend.

However, many hydrologic quantities are changing over the long term. Matalas (1997) questioned the assumption of stationarity within flood models given that temperature trends will create hydrologic trends that are not reflected in the models. Milly et al. (2008) proclaimed that "stationarity is dead" in reference to water management systems that historically assumed a known range of variability. A literature review by Lisonbee et al. (2024) and a technical report by Parker et al. (2023) showed that non-stationarity complicates the interpretation of nearly all aspects of drought, including the use of drought indices and anticipation of drought impacts.

In this perspective paper, we propose a series of priorities to navigate these complexities and progress drought science within a non-stationary climate system. Within this paper we use the term "drought" to describe a temporary period of abnormally dry weather leading to hydrological imbalance—an event or episode that has a beginning and an end. We use the term "aridification" to describe a climate that is trending drier and "humidification" to describe a climate that is trending wetter. In contrast to drought, aridification and humidification imply a change that is apparent over timescales long enough to necessitate adaptation to the new condition. Aridification and humidification complicate drought assessment in different ways.

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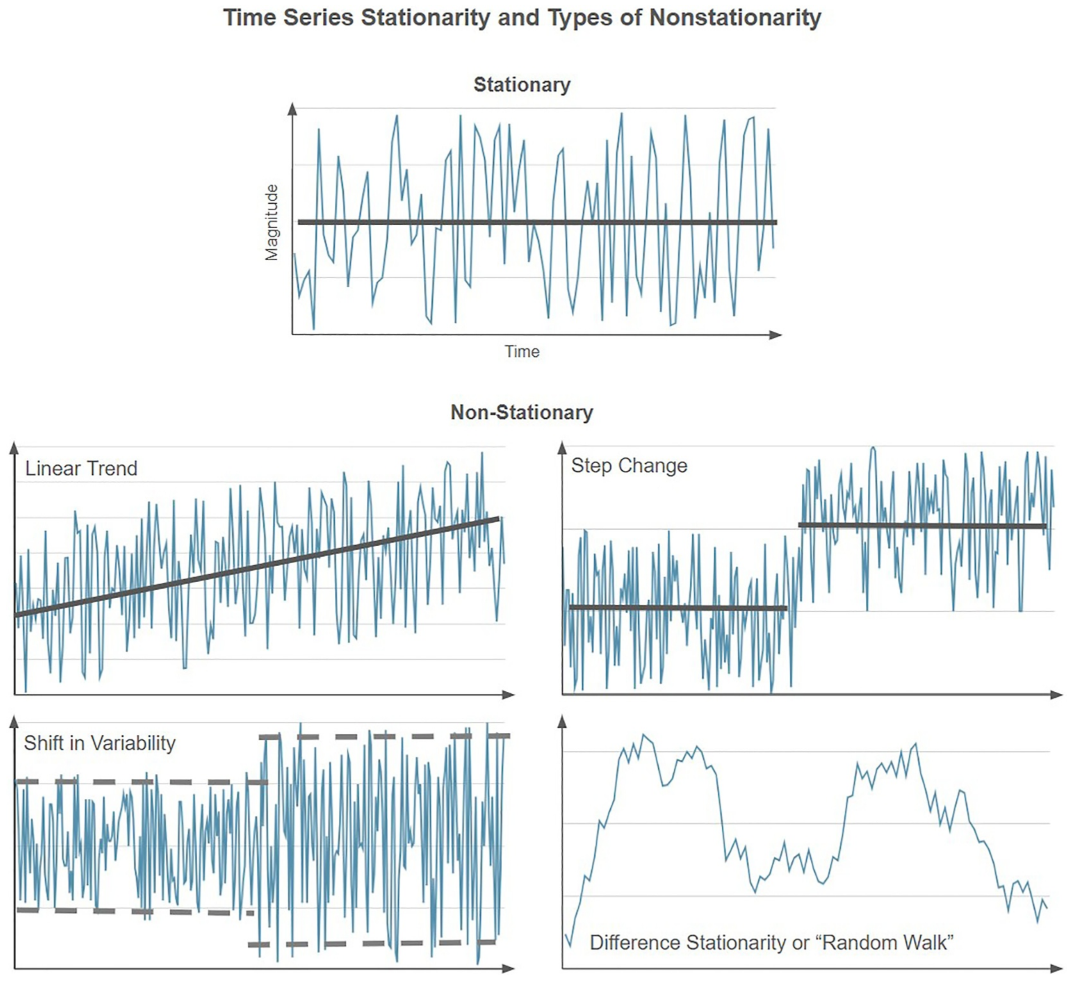

Figure 1. Examples of a stationary time series (top) and four types of non-stationarity that may influence drought assessment: a linear trend (center left), a step change (center right), a shift in variability (bottom left), and a random walk (bottom right). Figure adapted with permission from Salles et al. (2019).

Accurate drought assessment—the analysis and characterization of drought severity, extent, duration, drivers, impacts, or dynamics—supports community preparation, mitigation, adaptation, and response to drought. More accurately characterizing drought and acknowledging the impact of a warming global climate on drought frequency, severity, and impacts can enable communities, decision makers, and the public to better understand current and future risk, improve drought planning to build resilience, and avoid maladaptation.

Drought assessments that assume stationarity in a non-stationary climate have economic ramifications and can heighten the compounding and cascading risks of drought. For example, if no action is taken to account for non-stationarity in drought metrics, there will be significant increases in United States (U.S.) federal disaster assistance program expenditures, particularly through the Livestock Forage Program, which are expected to increase by 45%–135% (not accounting for inflation) by 2100 (Hrozencik et al., 2024).

As another example, the physical connection between drought and wildfire is generally understood (Littell et al., 2016; Riley et al., 2013). Changes in drought patterns are contributing to documented increases in the frequency, intensity, and size of wildfires worldwide (Abatzoglou & Williams, 2016; Iglesias et al., 2022; Liu et al., 2010, 2021; Meyn et al., 2010). The prevalence of abnormally large wildfires is also increasing over time across the western U.S. (Weber & Yadav, 2020). Not accounting for climate change in the connection between drought and wildfire can lead to missed opportunities to support adaptation in locations where changes in drought patterns are particularly rapid or where episodic droughts are compounded by a shift toward aridification or land degradation.

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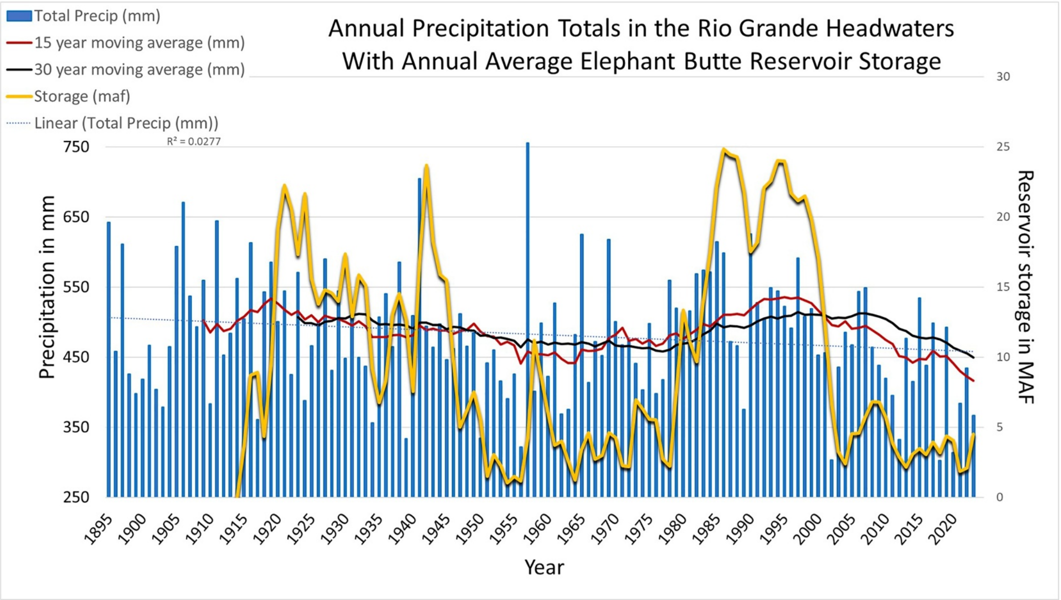

Figure 2. Left axis: precipitation (mm) in the Rio Grande headwaters over the past 125 years (blue bars) with a linear trend over the full period of record (dotted line), 30-year moving average precipitation (black line) and 15-year moving average (red line). Right axis: Elephant Butte Reservoir storage levels since 1915 in million acre-feet (yellow line). For data sources, refer to the Data Availability Statement.

Water storage at Elephant Butte Reservoir on the Rio Grande (New Mexico, USA) illustrates the impacts of non-stationarity within a managed system (Figure 2). Overall reservoir storage is influenced by precipitation in the headwaters of the Rio Grande, temperatures and evaporation, and sedimentation. If reservoir storage is used as an indicator of hydrologic drought, then one should account for not only those three components of change but the appropriate duration of a reference period (full period of record, 30-year WMO normal, or a 15-year optimal climate normal).

Adjusting drought assessment practices to account for climate change is also complex. Some adjustments may correctly capture the abnormality of the dry weather while not correctly capturing the severity of the drought. In an aridifying climate, for example, comparison of a dry period to a past, wetter climate will overestimate the abnormality because "normal" has become drier. Drought severity may still be assessed accurately unless human or natural systems already have adapted to the changing climate.

In some regions (any area, of any size, with shared attributes that is defined on the basis of the requirements of a drought assessment), climate change is blurring the lines between prolonged drought and long-term, or seemingly permanent, aridification. Farmers, pastoralists, foresters, and other land managers worldwide are repeatedly told that they are being negatively impacted by climate change that they cannot control (Backlund et al., 2008; Mbow et al., 2019; OXFAM, 2024). However, in many cases, reductions in soil water availability result from increased runoff and decreased soil water holding capacity due to land degradation, which humans can control (Bossio et al., 2010). A better understanding of where, how, and the extent to which aridification is resulting in changes in precipitation and evaporative demand can empower land managers and policy makers to recognize the costs of land degradation and the benefits from investments in soil conservation and improving soil health. Furthermore, the ability to differentiate between a temporary drought and a long-term change in water availability informs development of short-term conservation or long-term adaptation strategies.

Climate change has impacted the reliability of weather and seasonal climate information and assessments needed for decision making. Evidence suggests that global teleconnections with decadal, annual, and seasonal-to-subseasonal climate drivers, such as the El Niño-Southern Oscillation (ENSO), are changing (Collins et al., 2010; Power et al., 2013). The narratives based on climate drivers often inform planning decisions within the context of climate variability.

The challenges of drought assessment within a non-stationary climate system go beyond physical climate change to include changes in global human systems. Increases in human population size, the proportion of the human population that lives in urban areas, food and water insecurity, and cascading natural hazards are compounding and increasing economic losses and humanitarian assistance costs. In many low-income countries, severe droughts lead to famine. The United Nations (UN) Food and Agriculture Organization reported that in 2022, 691–783 million people faced food insecurity (FAO et al., 2023) from drought and other causes. In the U.S., drought cost an average of $8.2 billion a year from 1980 to 2024 (adjusted to 2024 dollars), primarily from agriculture loss (NOAA-NCEI, 2024). In Europe and the United Kingdom, drought cost an average of €9 billion per year from 1981 to 2021 (2015 euros) (Naumann et al., 2021), and costs are expected to increase to more than 65 billion €/year by 2100 as a result of the warming climate (Naumann et al., 2021). The damage and costs resulting from a drought tend to be greatly underestimated due to widespread and cascading impacts that often are not explicitly attributed to the drought (UNDRR, 2021). The social impacts of drought can include economic costs, food insecurity, famine, adverse health effects, exacerbated gender disparities, civil unrest, conflict, and migration (UNDRR, 2021).

Addressing the complexities of drought in a changing climate, including compounded and cascading impacts, offers multiple opportunities to improve drought risk assessments, planning, and response in support of the goals of the 2030 Agenda for Sustainable Development. Improving risk assessments and perceptions is a high priority in international forums and mechanisms for addressing climate change, such as the UN Framework Convention on Climate Change, Paris Agreement adaptation strategies, Sendai Framework on Disaster Risk Reduction, and aligned goals of the Convention on Biological Diversity and UN Convention to Combat Desertification (UNDRR, 2021).

NOAA Technical Memorandum OAR CPO 002 (Parker et al., 2023) provides 172 research questions (RQs) and priority actions (PAs) to better incorporate non-stationarity into drought assessment. Here, we provide our perspective on what we deem the 10 highest-priority items (methods described in Supporting Information S1), clustered by focus areas. From the 172 RQs and PAs, we selected the 10 that will promote science with the greatest potential to improve drought resilience and inform adaptation to a climate where the characteristics of droughts differ from those in the past. For each priority, we present ideas for implementation and describe the value of action and the cost of either inaction or taking the wrong action. We outline the steps needed to conduct the research or realize the actions, and identify measures of success for assessing advances in drought science given climate non-stationarity.

2. Priorities for Future Research

We present the 10 highest-priority RQs and PAs, with their ranks, grouped in the context of their focus areas as described in Parker et al. (2023). These are the RQs and PAs that we believe to be the most important for the advancement of drought science. Some of these priorities are closely related, and where possible we grouped them. Some of the priorities were not directly related, but could be used to support one another; in these cases we refer to supporting sections.

2.1. Improving Drought Indicators to Account for Non-Stationarity

> RQ: How can non-stationarity be addressed while adequately sampling the full range of drought variability? What existing or new methods can address non-stationarity? (rank 1)
>
> RQ: How have drought intensification rates (and recoveries) changed during the past few decades? How could they change in the future based on model projections? (rank 3)
>
> PA: Conduct a drought indicator intercomparison project that assesses drought indicator efficacy for decision making in a changing climate. (rank 7)

The items that ranked first, third, and seventh as RQ or PA priorities were related to drought indicators. We grouped these together because the background and motivation for each are closely related.

Drought indices and statistical models are sensitive to non-stationarity (Hoylman et al., 2022; Lisonbee et al., 2024; Sofia et al., 2024; Stevenson et al., 2022), which can be attributed to both natural climate variability and anthropogenic climate change. The climatological reference period used to determine drought intensity and frequency influences the assessed magnitude of current drought conditions, in part because common assumptions of stationarity may be violated over longer reference periods. Erroneously assuming stationarity may contribute to statistical bias in drought indicators (Milly et al., 2008) and an overestimation or underestimation of drought intensity when traditional probabilistic models are applied (Hoylman et al., 2022). We argue that methods describing non-linear patterns of climate change or the selection of appropriate reference periods for the system of interest could help accurately characterize contemporary drought intensity and frequency, and project future drought occurrence and impacts. An intercomparison of methods to identify drought properties over recent decades could also improve understanding of the effects of non-stationarity on drought identification and prioritization of methods for future use in drought declaration.

Use of a more recent climatology (e.g., the last 30 years) is a simple way to represent contemporary conditions, but will exclude major drought events that occurred prior to that reference period and may fail to capture multi-decadal oscillations in the climate system. Therefore, use of recent climatologies can limit the ability to identify rare, unexpected events with serious social consequences. Furthermore, a single reference period is unlikely to suit all situations given the heterogeneity of climate change and system-specific variation in adaptive capacity, hydrological context, or social and economic policies. More complex drought models can be used to explicitly model temporal dependencies and non-stationarity (e.g., Generalized Additive Models for Location, Scale, and Shape; Shao et al., 2022; Wang et al., 2015). However, these models are complex and challenging to integrate into operational drought monitoring systems at the national or global scale. Adopting new drought assessment methods may confuse practitioners and the general public even if accompanied by effective communication strategies (Cammalleri et al., 2022).

We argue that coordination at multiple levels of government could help advance approaches that account for non-stationarity in drought metrics and assessments and facilitate incorporation of new methods into existing assessment frameworks when appropriate. We suggest developing communication campaigns targeted to the diverse groups engaged in and affected by drought assessment that explain the differences between temporary anomalies (drought) and long-term changes (humidification, aridification).

Accurately characterizing drought and drought intensification rates in an era of climate change is critical to mitigate drought impacts to agriculture, water management, ecosystems, and society as a whole. Implementing drought assessments that distinguish drought from long-term changes in climate (both aridification and humidification) could help mitigate the impacts of drought on crop yields and production (Chatrchyan et al., 2017) while emphasizing the value of prioritizing adaptation to long-term trends (Anderson et al., 2020; Lal et al., 2012).

Furthermore, the frequency of flash droughts, characterized by rapid intensification over several weeks (Otkin et al., 2022), is projected to increase across many parts of the world by the year 2100 (Christian et al., 2023; Yuan et al., 2023). We believe that drought indicators that can identify flash droughts in a changing climate will be essential for accurately assessing future drought impacts.

New monitoring tools will enable adaptive decision-making regarding planting schedules, irrigation, crop selection, and livestock stocking rates (Coppock, 2020; Shrum et al., 2018; Zhang et al., 2015). Statistical models for drought assessment that account for non-stationarity and separate identification of long-term trends would facilitate understanding of and responses to evolving climate patterns and trends (Borgomeo et al., 2014; Dettinger et al., 2015; Milly et al., 2008; Salas et al., 2012; Vogel & Kroll, 2021; Zhao et al., 2018), enabling more effective water allocation, reservoir management, and conservation strategies (Brown et al., 2019; Hanak & Lund, 2012; Miller et al., 1997; Stakhiv, 2011; Vano et al., 2018) and potentially reducing competition among water demands and water uses.

2.2. Evaluating Drought Impacts and Their Trends

> RQ: What is the relationship between assessed drought conditions, antecedent conditions, and drought impacts? Can these criteria be adjusted to account for a changing climate given that impacts are not stationary due to changes in land management, resilience to extremes, technological changes, or changes in the relationship of climatic factors (e.g., relationship between temperature and water availability)? (rank 2)

Table 1
Illustrative Types and Temporal Extents of Drought

Type	Definition
Agricultural	Meteorological and hydrological drought that adversely impacts agricultural production
Hydrological	Prolonged meteorological drought that affects surface or subsurface water supply
Meteorological	Lack of precipitation, or evaporative demand that exceeds precipitation, for a prolonged period
Ecological	Changes in ecological state caused by deficits in water availability
Temporal extent	
Flash (subseasonal)	Rapid-onset periods of elevated surface temperatures, low relative humidities, precipitation deficits, and a rapid decline in soil moisture
Seasonal	Drought that occurs during part of a given year and may occur in successive years
Multiple-year	Drought that persists for more than one water year[a]
Megadrought	Drought that persists for multiple decades

Note. These definitions do not account for interactions between drought types or the cascading or long-term impacts that may result from drought. [a]A water year is a 1-year period from October 1st through the following September 30th and is named for the year in which the period ends.

Drought conditions are often assessed through the lens of their impacts. However, as this RQ suggests, drought can impact the same population or location differently over time as mitigation measures are implemented. Current drought assessment methods identify anomalous conditions and impacts relative to reference periods. Doing so assumes that a drought today and a drought of equal magnitude 30 years ago will have the same impacts. However, reference periods of 30 years or longer may be insufficient to account for the impact of non-stationarity in drought conditions that result from rapid changes in climate, land use, or technology. It is common to categorize different types of drought, such as meteorological, hydrological, agricultural, ecological, and socioeconomic, on the basis of their effects on particular components of human and natural systems (NIDIS, 2021). This approach can be used for discussing drought, but can introduce bias and maladaptation because drought types can overlap and interact (Table 1).

Multiple metrics are applied to assess drought severity with respect to different aspects of a given sector's need for water (WMO and GWP, 2016). Prior to development of the Drought Impact Reporter (Wilhite et al., 2007), data on drought impacts generally were linked to crop losses and did not represent effects of drought on multiple sectors. Despite the increasing diversity of data on drought impacts, the data still have sectoral biases. For example, they rarely account for non-agricultural costs or losses. The data also do not clearly differentiate direct and indirect impacts and do not explicitly reflect non-stationarity. Therefore, it is difficult to understand whether the characteristics of future droughts, such as their intensity and duration, are likely to be similar to those of past droughts, and in turn whether the effects of future droughts are likely to be similar to those of historical droughts. This difficulty reflects not only changes in the atmosphere and physical environment but changes in social and economic systems, policies, and adaptive capacity. For example, drought in the Southern Plains region of the U.S. during the 1950s was more severe in physical terms than drought during the 1930s, but the agricultural, economic, and social effects of 1950s drought were milder (Wiener et al., 2016).

Drought declarations, or relief actions that are based on the impacts of drought, exemplify the benefits of understanding the cascading effects of a non-stationary climate on water availability. For example, the U.S. Drought Monitor, which incorporates impacts to some degree (Table 3 in Svoboda et al., 2002), informs administrative drought declarations that trigger financial relief and crop insurance programs for agricultural producers. Drought declarations at state, county, and municipal levels often are based not only on physical indicators of drought but on the effects of drought on social and economic priorities, from municipal water use to irrigation. For example, the Washington State Drought Contingency Plan focuses on emergency responses to the effects of drought on water supply on the basis of forecasted runoff below the state's statutory threshold and the risk of undue hardship for water users and the environment (Revised Code of Washington Drought Conditions, 2024; Washington State Department of Ecology, 2018). Accurate assessment of both drought conditions and drought impacts is essential to ensuring economic and social support for sectors that are most strongly affected by drought.

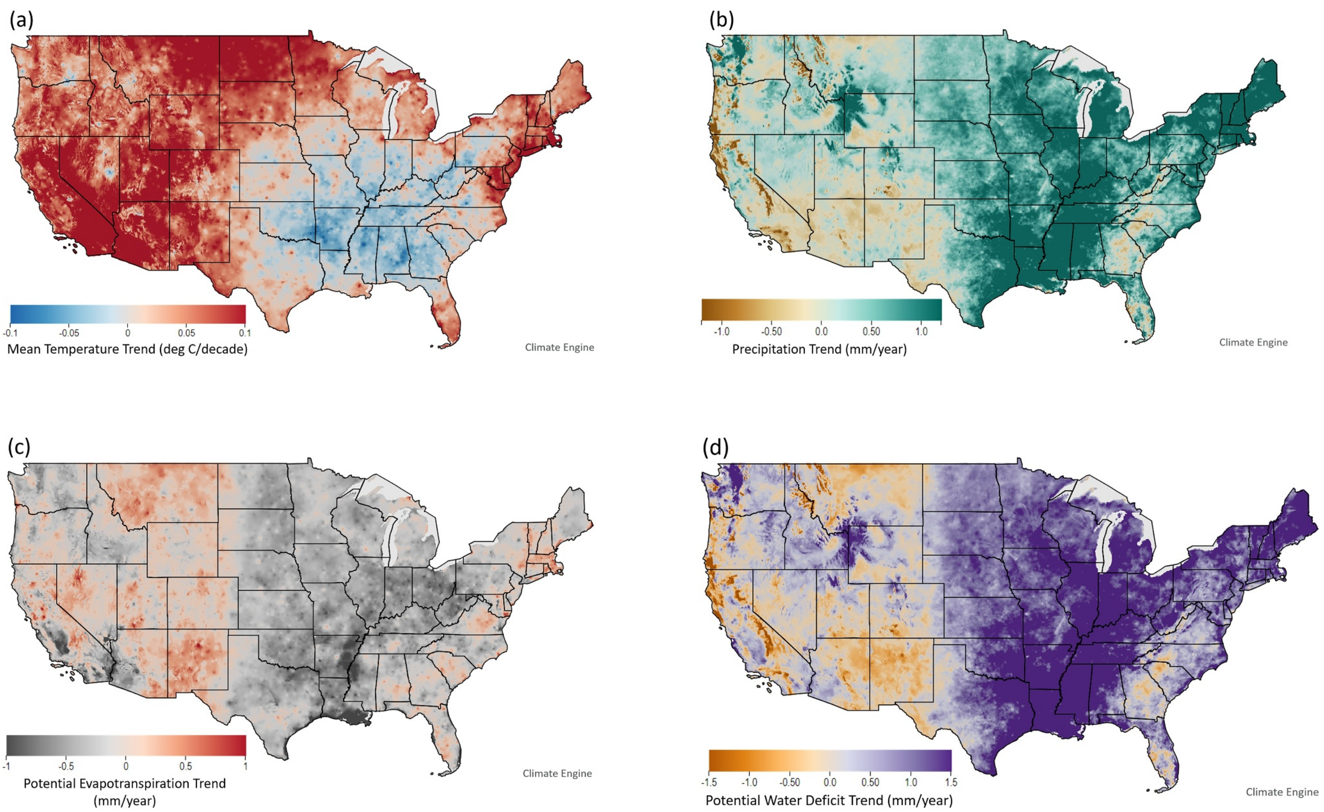

Figure 3. Sen's slope of annual (a) mean temperature in degrees Celcius per decade, (b) total precipitation in mm per year, (c) total potential evapotranspiration (PET) calculated with the Hargreaves PET estimate in mm per year, and (d) potential water deficit (P-PET) calculated with the Hargreaves PET estimate in mm per year. The period represents 128 years from 1895 through 2023. Data from the PRISM 4-km monthly precipitation data (PRISM Climate Group & Oregon State University, 2024). Maps created with ClimateEngine.org (Climate Engine, 2024; Huntington et al., 2017).

Ideally, the criteria used to assess drought can be adjusted to account for climate change, thereby recognizing that both drought conditions and the impacts of drought may be non-stationary. As noted in this RQ, such non-stationarity may be due to any combination of climate change and changes in human activity, resilience to extremes, technology, or relations among elements of climate. Adaptation of drought criteria requires selecting reference periods that account for local or regional trends; documenting impacts of drought and their responsiveness to drought severity, duration, and intensity relative to place-based reference conditions; and revising definitions or concepts of drought to account for the effects of drought on people. Multiple criteria for drought are warranted to classify drought in a changing climate. By evaluating drought impacts and their trends, and adapting to those trends, society could become better prepared for conditions that are anomalous relative to the reference period.

2.3. Addressing Regional Differences in Non-Stationarity

> PA: Evaluate and compare current drought indicators to determine if they depict drought conditions appropriately and effectively given regional differences in non-stationarity. (rank 4)
>
> RQ: How is regional variability of drought indicators changing over time and with climate change? (rank 8)

The RQs and PAs that ranked fourth and eighth related to regional differences.

Drought manifests differently in different ecosystems and regions. For example, compare drought in a temperate rainforest in southeastern Alaska (Bathke et al., 2019) with woodlands in the southwest U.S. (Breshears et al., 2005). Warming rates and mean precipitation changes, including changes in precipitation variability and drivers, differ among regions (Figure 3). These discrepancies contribute to regional differences in historic, current, and projected drought conditions (onset, duration, area, and intensity) and to the seasonality, frequency,

Table 2
Regional Drought Trends and Research Questions

Region	Drought trend	Regional research questions
Southwest	Decreased SPEI, some areas with no clear trend	How is seasonality and geographic variability incorporated into the assessment of drought impacts?
Northwest	Increased SPEI, with a decrease in some climate divisions	How are intra-regional differences in drought conditions considered during assessment?
Northeast	Increased SPEI	How can precipitation effectiveness be considered when assessing drought conditions?
Southeast	Increased SPEI, with a decrease in some climate divisions	Are the contributions of solar radiation and evapotranspiration incorporated into drought indices?
Outside CONUS	Trends mixed in Alaska, decreased SPI in Hawaii, decreased SPEI in U.S. Caribbean, some decreases in SPI in USAPI	What information is necessary to include these areas in current CONUS climate products?

Note. Drought trends for the CONUS are based on the average rate of change in the 5-year Standardized Precipitation Evapotranspiration Index (SPEI; Vicente-Serrano et al., 2010) from 1900 through 2022 (Figure A4.9 in Stevens et al., 2023). Reported drought trends for OCONUS locations [US Caribbean, Alaska, Hawaii, and US-Affiliated Pacific Islands (USAPI)] are based on calculation of local SPEI and the Standardized Precipitation Index (SPI; McKee et al., 1993; Frazier et al., 2022; McGree et al., 2016; Sorí et al., 2021; Walston et al., 2023). Example regions in this table are approximately defined by dividing the CONUS into quarters and are meant to be illustrative only.

cycle, uncertainty, management, and impact of drought. The ability of drought indicators to capture regional differences in drought trends and variability is influenced by the extent and resolution of data and variation among ecosystems and land uses. Climate non-stationarity likely influences regional drought index values and the way drought is manifesting across space and time (refer to Section 1). Therefore, drought indicators should be chosen that account for non-stationarity and characteristics of the region.

Climate trends differ among regions and lead to different research questions (Table 2). Within the Northern Plains region of the U.S., the Eastern Plains (Dakotas) have become wetter, while the Western Plains (Montana and Wyoming) have become drier. Treating these states as a single region dilutes those trends (Easterling et al., 2017). The midwest U.S. is wetter than pre-1980, whereas the southwest U.S. is in a multidecadal drought (Hudson et al., 2022). Reported drought trends for the contiguous U.S. (CONUS) are based on the average rate of change in the 5-year Standardized Precipitation Evapotranspiration Index (SPEI). Reported drought trends for U.S. regions that are outside CONUS (OCONUS; U.S. Caribbean, Alaska, Hawaii, and US-Affiliated Pacific Islands) are based on calculation of local SPEI and the Standardized Precipitation Index (SPI).

Climate variability also drives regional differences in drought magnitude and frequency. For example, ENSO is a strong regional driver of drought in Hawaii, the U.S.-Affiliated Pacific Islands, and the western U.S. (e.g., Frazier et al., 2019, 2022; Zhang et al., 2012). Ecological differences among regions can further contribute to differences in regional climate variability through land-atmosphere feedbacks mediated by plant functional types (Anderegg et al., 2019). Differences among plant species' ability to shift their distribution or otherwise adapt (Clark et al., 2016; Moss et al., 2024; Sharma et al., 2022) exacerbates regional climate vulnerability and impacts. As climate changes, temporal and geographic shifts in climate drivers and their impacts are projected to continue (e.g., Cai et al., 2021; refer to Section 2.4). Changes in these drivers may also contribute to forecasts and early warning, which can provide opportunities to improve responsiveness, potentially mitigating negative impacts (e.g., Kelman, 2019; Schroeder et al., 2012).

Uncertainty can vary regionally by drought indicator depending on the observational data used to contextualize more recent conditions. For example, the estimated severity of drought in Alaska varies considerably among indexes (Walston et al., 2023). The data available for OCONUS regions is severely constrained compared to that available for CONUS. These data limitations can constrain drought identification and response (Basile et al., 2024; Frazier et al., 2023; Méndez-Lazaro et al., 2023). Many drought indices, such as the Evaporative Demand Drought Index (Hobbins et al., 2016), Crop Moisture Index (Juhasz & Kornfield, 1978), Vegetation Drought Response Index (Brown et al., 2008), and products derived from the gridMET (Abatzoglou, 2013) and

Climate Divisions data, are only available for CONUS. Hawaii recently established state climate divisions that can facilitate future inclusion of the state in gridded climate products (Luo et al., 2024).

Certain drought indices may bias representation of drought impacts, especially in humidifying regions such as the northeastern U.S. (Li et al., 2024). When these indices are paired with financial subsidies, there may be regional discrepancies in needed and delivered support. To best quantify the impacts of drought non-stationarity on social, economic, ecological, and cultural systems, regional context is required. Applying more regional context in the development of drought indices is needed to improve local utility and reduce bias. Providing regional context requires building and maintaining local and regional partnerships for better coordination and communication (Elias et al., 2023; Longman et al., 2022). Regions also experience varied drought impacts due to differences in economic sectors, cultural practices, and ecosystems, which complicates efforts to determine which drought indicators to select when prioritizing adaptation and mitigation efforts within and across regions.

As management strategies adapt to wetter or drier conditions, regional drought risk profiles may change. Exposure and sensitivity, two aspects of vulnerability to drought, are regionally clustered, whereas adaptive capacity is more dependent on jurisdiction (e.g., state or county), with some regional clustering (Engström et al., 2020). Some non-stationary drought impacts can be regionally clustered by dominant social, economic, and ecological systems. For example, understanding ecological impacts of drought on forests may require longer reference periods than understanding impacts on grasslands. Management strategies are further complicated when managing systems that span multiple regions and could be designed to consider various vulnerabilities.

Although not directly related to drought assessment in a non-stationary climate, flexible seasonal definitions would allow for consideration of changes in precipitation variability within specific regions (refer to Section 2.5). Analyses of regional differences among drought indicators could allow for flexible definitions of seasons across space, such as in parts of the southwest U.S. where species have evolved in response to the bimodal seasonality of precipitation.

Another consideration is that CONUS locations tend to have longer weather records than OCONUS locations. To avoid differences in data coverage among regions, researchers can assimilate local climate data into drought indicators with broader spatial coverage. For instance, the high-resolution gridded climate products developed by the University of Hawai'i provide statewide precipitation data from 1920 to present, along with data on several other variables (Frazier et al., 2016; Longman et al., 2024).

When evaluating and comparing current drought indicators, we recommend following the guidance of Redmond (2002). Among the goals of evaluating drought indicators are examining whether multiple indicators yield the same drought characterization in a given location, whether a given indicator is equally reliable in regions that are changing in different ways, and whether drought indicators depict conditions in a given location appropriately and effectively given regional differences in non-stationarity. Ideally, evaluations can identify the optimal drought indices and the appropriate spatial scales for calculating them. The evaluations can also be used to measure uncertainty in the drought assessment outcomes, such as when drought indicators yield different conclusions on the basis of regional variation. Overall, evaluating the regional utility of drought indicators can inform, or cause reconsideration of, future application of those indicators.

2.4. Determining the Physical Drivers of Drought and How They Are Changing

> RQ: Improve understanding of how rising temperatures interact with the water cycle to influence drought. Are the relationships stable in a changing climate, or are they projected to change? Does a changing baseline mean that it is getting harder to get out of drought? (rank 5)

Physical drivers of drought include any climate phenomena that can create persistent weather patterns and cause droughts to form, intensify, ameliorate, or end. How these physical drivers, including land-atmosphere feedbacks, will change in a warming climate is a source of significant uncertainty. Therefore, advancing understanding of how climate change affects the mean state and variability of all components of the hydrologic cycle and their complex relationships can facilitate interpretation of future hydrologic cycle anomalies and droughts and subsequently guide development of tools, assessments, and planning. Here, we examine challenges to drought assessment in a changing climate arising from the demand side of drought—evapotranspiration, evaporative demand, and land-surface processes—and strategies for overcoming these challenges (we examine precipitation as a driver of the supply side of drought in Section 2.5).

Physical process understanding of evapotranspiration and evaporative demand for drought assessment requires moving beyond a solely temperature-based focus. Air temperature is generally a major driver of evaporative demand, evapotranspiration, and demand-induced anomalies in the hydrologic cycle (Hobbins, 2016; Huntington, 2006). At the local land surface, these anomalies are primarily caused by the Clausius-Clapeyron relationship (e.g., Alduchov & Eskridge, 1996), which raises the saturated vapor pressure in response to warming air temperature. All else equal, this increase in the moisture-holding capacity of the air (or vapor pressure deficit) is reflected in increased evaporative demand. At regional and larger extents, circulation patterns are affected by trends in global temperatures (e.g., Mann et al., 2017). However, air temperature is not the only driver (e.g., Hobbins et al., 2008). For example, over a recent 30-year period (1981–2010), the variability of summer evaporative demand is dominated by wind in the southwestern U.S. and solar radiation in the southeastern U.S. (Hobbins, 2016). Therefore, it is important to understand climate change-induced shifts in the mean state and variability not only of temperature but of humidity, radiation, and wind. The roles of internal variability and anthropogenic climate change must also be diagnosed and differentiated on all drivers of evapotranspiration and evaporative demand.

Looking at longer, climate-scale changes, Figure 3 demonstrates 128-year trends in evaporative demand derived from a solely temperature-based Hargreaves formulation of PET. Extending observational PET that far in time is only possible using a temperature-based approach, as data on the other drivers of evaporative demand are not available or reliable at those temporal extents. This underscores one of the limitations on long-term analyses of the demand side of drought: results so derived are heavily influenced by the trends in temperature. Nevertheless, a holistic understanding of land-surface processes and their role in the hydrologic cycle remains vital for drought assessment in a changing climate.

Agriculture and ecological processes depend on soil properties and therefore on land-atmosphere feedbacks. Degradation of soil structure can dramatically influence runoff, infiltration rate, and plant-available soil water capacity, and thereby significantly impact the hydrologic cycle and its response to climate change and internal climate variability (refer to Section 2.5). Understanding the impacts of soil variability and land degradation on soil processes is critical for agricultural and ecological drought assessment in a changing climate. Land degradation includes soil degradation and changes in plant community composition, cover, and structure, all of which can reduce soil water infiltration.

Drought research and assessment that incorporate evapotranspiration and evaporative demand can be improved by considering all drivers of evapotranspiration and evaporative demand. Often, evaporative demand parameterizations have used temperature as a proxy for all drivers. The use of temperature-based proxies for the demand side of drought has been pervasive, likely because temperature observations are ubiquitous and have long records. However, this would not be considered best practice by today's standards (Donohue et al., 2010). Metrics of evaporative demand that also include wind, solar radiation, and humidity could provide a more accurate picture of water availability.

Beyond evaporative demand, to improve understanding of how rising temperatures interact with the water cycle to influence drought, observations and models should include the full suite of drivers and their impacts on the hydrologic system. This includes direct observations or physical modeling of land and atmosphere processes, which have historically been challenging to measure, model, and predict. Recent studies have increasingly called for more explicit observations, simulations, and projections of soil moisture, runoff, streamflow, and groundwater dynamics to represent drought impacts in a changing climate (Ault, 2020; Berg et al., 2017; Berg & Sheffield, 2018). We agree that explicit observations, simulations, and projections are usually preferred over meteorological drought indicators that are based only on precipitation or temperature. Drought processes may not be depicted accurately when considering only precipitation inputs and evaporative demand, but not soil infiltration rates, the soil's plant-available water storage capacity, or the water requirements of vegetation (including crops and forage) at different times of the year.

Physical process understanding of the hydrologic cycle and its response to climate change can improve drought monitoring, prediction, projection, and assessment in all regions and sectors. Addressing the RQ in this section would benefit consumers of drought forecasts, those directly impacted by drought, and scientists who study drought by improving effective monitoring and short-term prediction of drought impacts across sectors. Improved monitoring and prediction would enable adaptation to future drought through better planning, policy, and both traditional and nature-based infrastructure solutions. For example, a better understanding of the relationship among

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changes in supply, demand, and land degradation would be greatly beneficial for targeting investments by farmers, ranchers, development organizations, and governments in soil conservation and land management and restoration. The cost of inaction in this area is a dearth of knowledge on what drives drought and its non-stationarity. Such lack of knowledge will likely increasingly constrain the ability to interpret drought and anticipate its impact and future behavior, which in turn will likely limit the development of tools for proper drought assessment, adaptation, and impact mitigation. Success measures of adaptation and mitigation actions will depend on industry or sector. For example, in agriculture, success might manifest as an increase (or at least no decrease) in yield stability for farmers, and especially for those who farm small areas in drylands. We recognize that success also depends on the availability of alternatives, such as drought-adapted crops and management systems that improve soil health, that can be implemented in response to the knowledge and information generated by these research efforts.

2.5. Applying Precipitation Effectiveness to Capture Precipitation Variability

> PA: Develop a better understanding of how drought duration and rate of intensification might change in the future due to changes in meteorological drivers and vegetation properties. This includes a better understanding of hydrologic cycle intensification (e.g., fewer but larger magnitude precipitation events and more rapid transition between high and low precipitation extremes) and policy implications of these changes. (rank 6)

Precipitation is key to understanding drought processes; however, understanding how that precipitation is partitioned among other branches of the hydrologic cycle, including runoff, infiltration, and subsequent plant use, is important for a comprehensive understanding of drought and its impacts. As mentioned in Section 2.4, much of the existing drought monitoring infrastructure is largely dependent on assessing precipitation- or temperature-informed drought metrics and then translating these metrics to possible impacts on soil moisture, streamflow, and groundwater. Understanding, measuring, and modeling the physical hydrology and its relationship to drought is also necessary to help constrain uncertainty in projections of changing drought characteristics (refer to Section 2.4). Drought monitoring infrastructure that is responsive to changes in regional climates (such as expanded soil moisture monitoring networks; NIDIS, 2024) and the associated drought impacts would facilitate an improved understanding of how drought duration and rate of intensification may change in the future, leading to more explicit consideration of how precipitation and precipitation variability affect the various components of the hydrologic system.

Many drought indices, including the SPI and SPEI, cannot capture precipitation variability over short periods of time because they consolidate precipitation over longer periods, usually 30-day aggregations (30-, 60-, 90-day SPI, etc.). This consolidation obscures the frequency and intensity of precipitation events—whether the precipitation came in several small events or one large event. This distinction can be important for drought assessment because precipitation frequency and intensity affect soil infiltration, runoff, and surface water supply. Therefore, precipitation effectiveness may be a useful concept for capturing precipitation variability. Precipitation effectiveness has multiple definitions and terms, but it can be understood as the usefulness of precipitation within a given system (Parker et al., 2023 and references therein). Metrics of precipitation effectiveness include runoff, soil moisture, groundwater, and evapotranspiration. Although shortcomings and challenges are associated with the concept of precipitation effectiveness (Parker et al., 2023), it offers potential for better characterizing drought at local and regional scales and the impacts of drought on agriculture, ecosystems, and water resources. This framework, when viewed through the lens of a changing climate, may provide a means to monitor drought in a scenario of more intense and less frequent precipitation.

From a supply-demand perspective, precipitation effectiveness can more accurately quantify water supply to a landscape, accounting for the influence of precipitation intensity and runoff ratios. Similarly, increasing temperatures can influence the demand side of the supply-demand equation. Increases in temperature enhanced evaporative demand for transpiration and soil evaporation despite increased water use efficiency in some plant species in response to increasing atmospheric CO_2 concentrations, which can partially offset higher evaporative demand (Scheff et al., 2021; Swann et al., 2016). The supply-demand model of drought dynamics remains valid and useful in a changing climate when properly accounting for all aspects of water supply to and water demand from a landscape.

Improving the accuracy of monitoring and modeling of all components and processes of the hydrologic system (Ralph et al., 2014) would enable a better understanding of precipitation effectiveness in a changing climate. The scientific community could continue to expand high-quality measurements of soil moisture, runoff, evapotranspiration, and groundwater globally, and ensure these observations are equitably distributed. High quality in situ and remotely sensed observations improve simulation of precipitation effectiveness and drought dynamics in different regions and can complement further model development, all while leveraging advances in machine learning and other forms of artificial intelligence.

Further research is needed to improve monitoring of agricultural and hydrological drought conditions across scales. Studies could consider the potential impacts of precipitation intensity and precipitation effectiveness on drought intensity, seasonality, duration, recovery, and the regional variability (refer to Section 2.3) of the complex processes driving drought. More accurate simulation of precipitation effectiveness can also help to refine predictions of droughts on actionable timescales and tangibly improve societal outcomes and climate resilience. Examples include subseasonal-to-seasonal (S2S) forecasts of streamflow extremes (e.g., 7-day low flow, peak spring flow) that could be used to plan for and mitigate the impacts of hydrologic droughts and floods. These advancements require transdisciplinary research frameworks that combine physical and social sciences to ensure that S2S predictions and uncertainty can be correctly interpreted, and are responsive to decision makers' constraints.

Additional research could improve understanding of how precipitation intensity and precipitation effectiveness respond to a warming climate. Climate and drought assessments that transcend siloed analyses of precipitation or days without measurable precipitation (dry days) could more holistically capture drought dynamics under potential future climates and possible impacts of these changes. Improvements in the measurements and projections of regional changes in precipitation intensity could provide greater insight to how those changes influence drought characteristics, while constraining the significant uncertainty inherent in projections. Direct projections of soil moisture, runoff, streamflow, and reservoir storage could lead to a better understanding of the impact of precipitation effectiveness on future drought and improve the utility of drought projections for planning and assessment.

The potential benefits of understanding and quantifying precipitation effectiveness extend beyond drought monitoring, with applications extending to areas such as agriculture, ecology, energy, water resource management, and wildland fire. Tangible outcomes could include improved timeliness in the identification of—and subsequent response to—drought, enhanced mitigation activities that reduce the overall impact of drought, or the development of effective drought plans (or hazard mitigation plans that include drought). Such outcomes will likely be dependent on the success of the drought research and monitoring communities in translating and communicating this challenging topic to decision makers, and how those decision makers use the information for mitigation and response. Any communication on precipitation effectiveness can acknowledge that climate change is impacting different regions in different ways and that future drought episodes may be different, especially in terms of timing and intensity, than previous episodes. Although the realization of a real-time metric for precipitation effectiveness may be many years into the future, maintaining the status quo propagates a deficiency in present drought assessment capabilities. Any advances toward a deeper understanding and quantification of precipitation effectiveness will likely lead to a more robust drought monitoring paradigm that could more effectively anticipate and assess conditions, and ultimately help build a more drought-resilient future.

2.6. Understanding Drivers of Aridification and Their Interactions With Drought

> PA: Provide a unified framework to define, identify, and quantify the drought-to-aridification continuum. This may include providing a timescale for how long a trend needs to be in place for it to be considered aridification. (rank 9)

Aridification is a long-term transition toward drier climatic conditions. The concept is most commonly applied to ecosystems in the context of the expansion of drylands. The most common metric of aridification is a long-term change in the ratio of precipitation to potential evapotranspiration, known as the Aridity Index. The Aridity Index is a measure of the relative scales of supply of moisture from the atmosphere to the surface (precipitation) and the demand for the return of that moisture (evaporative demand), the two sides of the drought equation. Climate models consistently project a global decline in the Aridity Index over land, driven by higher temperatures and the inability of evaporation rates to maintain a constant vapor pressure deficit (Park et al., 2018; Sherwood & Fu, 2014). Berg and McColl (2021) argued that the Aridity Index is merely an atmospheric proxy for aridification and does not track aridification well under climate change. A more direct ecological indication of aridification is a transition from an energy-limited evapotranspiration regime to a water-limited regime. Projections of such transitions also indicate a general drying trend globally (Denissen et al., 2022; Hsu & Dirmeyer, 2023). However, climate model projections of increased biomass suggest that such drying will not be accompanied by ecosystem shifts toward sparser vegetation, partly but not entirely due to changes in plant physiology caused by increased carbon dioxide concentrations (Scheff et al., 2021).

Overpeck and Udall (2020) argued that it is dangerous to interpret aridification as simply a trend in drought frequency or intensity. As mentioned in the introduction, a drought, by definition, has a beginning and an end. During a drought, one can be confident that precipitation will increase eventually. However, aridification implies a long-term change, which necessitates a transformation within ecosystems, and sometimes human systems.

Drought's definition as an impactful, but temporary, deviation of moisture status from more typical conditions raises the central question of the distinction between aridification and drought: how long must moisture conditions be abnormal relative to the past before they are considered aridification?

A simple approach to distinguishing between aridification and drought is to focus on impacts to human or ecological systems. If the impacts of a long-term drying process extend beyond the resilience of the system and lead to permanent change (e.g., ecological transformation, see Moss et al., 2024), then the drying qualifies as an aridification process. If the same impacted entity can return to previous condition or behavior, then the anomaly is drought. However, with this approach, the same climate occurrence might be classified as a drought for some populations, species, or groups of species, and aridification for others. For example, is the current lack of adequate water for human uses within the Colorado River basin a manifestation of a megadrought or aridification (Cook et al., 2022; Williams et al., 2022)? When should dry conditions be treated as temporary, and when should they be regarded as permanent or quasi-permanent? Whatever the distinction, a greater understanding of these issues will likely inform short-term drought responses and long-term water supply planning.

Whether aridification leads to more severe or frequent droughts depends on one's definition of drought (IPCC, 2012; Satoh et al., 2021). If drought is defined as a historically rare event, aridification will lead to more severe and more frequent droughts. To the extent that water-dependent systems have been designed or adapted to historical conditions, those systems will be stressed more frequently and more severely. If drought is defined as a rare event in the context of the current climate state, such as a dry anomaly with an annual exceedance probability of 20%, the frequency of drought remains unchanged. Nonetheless, the nature of those droughts would be different.

Parker et al. (2023) recommended that future research closely examine the relative importance of different drivers of aridification (global anthropogenic, local anthropogenic, long-term natural); we have identified this recommendation as a high priority. No matter the drought definition, aridification leads to major drought-like impacts, and it would be valuable to better differentiate aridification from drought at local and regional scales. A few unanswered questions include the following: During aridification, how do droughts change? Are "hot droughts" (Breshears et al., 2005; King et al., 2024; Overpeck, 2013) a manifestation of aridification projected onto droughts? Does aridification lead to changes in drought onset, duration, and recovery? Even if drought is defined by annual exceedance probability, the characteristics of droughts may be aridity-dependent, and better understanding of these issues may require adaptation of drought contingency plans and actions.

Ultimately, distinguishing between changing drought and aridification makes it possible to select the appropriate adaptation strategy. In the context of water supply, for example, if "normal" is unchanging but droughts are becoming longer, an increase in storage capacity may solve the problem. However, if aridification is taking place, a long-term decrease in demand or an increase in supply may be necessary.

2.7. Incorporating Non-Stationarity Into Drought Planning, Management, and Adaptation

> RQ: How does non-stationarity impact drought response triggers and thresholds and how can these be adaptive to changing conditions? What variation in drought triggers and thresholds exist between aridifying and humidifying climates? What adaptive drought management strategies need to be developed to address these variations? (rank 10)

The scale and methods for drought planning vary globally. In the U.S., drought planning falls within the scope of water resources, land use, and hazard mitigation planning. States are responsible for managing the water within state boundaries and complying with interstate agreements for shared surface and groundwater resources. As such, states are also responsible for state level water plans, drought plans, and hazard mitigation plans (National Drought Mitigation Center, 2024; Schwab, 2013; Stern et al., 2021; Wickham et al., 2019), and in some cases providing guidance for county-level or local drought planning. Stand-alone drought plans that focus on preparedness, mitigation, and response (Fu et al., 2013) are conducted at multiple scales, and across jurisdictions and sectors (e.g., water suppliers, utilities, and land use managers). Each of these sectors is governed by different policies and affected by distinct impacts, which influence actions for risk reduction.

Non-stationarity complicates drought planning in three ways. First, determining accurate drought thresholds and triggers in a changing climate is a fundamental component of adapting drought planning to address twenty-first century climate realities and drought impacts (refer to Section 2.1). Second, a lack of consistent regulation around drought planning means that drought plans, where available, may not be regularly updated to conform with a changing climate. Third, the regional variation and sector specific actions for drought vulnerabilities, coupled with different policies and governance structures, complicates effective adaptation and preparedness in a changing climate (refer to Sections 2.3 and 2.5).

Accurate thresholds and triggers are critical to drought planning, preparedness, and response. Modern plans can facilitate new adaptive practices within drought resilience strategies that may not have been necessary in the past. Ideally, thresholds and triggers for drought declaration and response will implicitly acknowledge that future droughts may be different (e.g., hotter) from past droughts. These improvements can include drought indicators, thresholds, and triggers that account for non-stationarity (refer to Section 2.1). Arid regions could particularly benefit from adapting water management practices to account for climatic shifts.

As drought indicators evolve to better account for non-stationarity, revising drought plans to incorporate these advancements likely will be important. Without regular drought plan updates, non-stationarity can potentially make dated drought plans ineffective or maladaptive (Li et al., 2024). Requirements for drought plan updates that are based on current climate data for the development of appropriate triggers and thresholds could improve drought preparedness and response. Alternatively, drought plan updates that are based on more relevant climate reference periods that capture the changes in potential risks (e.g., to critical infrastructure or economic sectors) could also improve future preparedness. As of April 2024, all but four states (Alaska, Arkansas, Louisiana, and Mississippi) have a stand-alone drought plan (National Drought Mitigation Center, 2024). Since 2015, 20 state drought plans have been updated for different reasons. For example, Massachusetts updates their drought plans after a drought event (Massachusetts Executive Office of Energy and Environmental Affairs, 2023). Only 10 of the 20 updated drought plans mention climate change. States are increasingly prioritizing drought and addressing climate change. However, there continues to be a disconnect between updating the plan and intentionally accounting for the influence of climate change on drought events or impacts.

Continued implementation of outdated drought plans, or the use of outdated triggers and thresholds in recent plans, can lead to maladaptive outcomes given changing climatic conditions. The increasing need for drought resilience highlights the urgency of improved data and understanding of climatic shifts due to climate change, and the application of that knowledge into drought planning and response. Including drought in hazard mitigation, water supply, and land use plans, which have update requirements, would facilitate consistency between drought planning and policies and changing climate conditions.

Drought conditions and impacts can vary greatly across geographic scales (jurisdictions), resources (land, water, air), and sectors (economic and governance). These variations create a diverse portfolio of drought risks and priorities for response (actions). Accurate, place-based drought triggers and thresholds are the foundation for drought preparation and resilience to future climate conditions. Often, planning efforts rely on data and resources provided by federal agencies, which are combined with state and local level data, objectives, and knowledge to determine planning priorities and policies. This creates broad variation in the geographic scales and sectors included in drought planning efforts within states and across states and basins, highlighting the need for consistency in the data and periods used for determining drought triggers and thresholds. Improving the guidance (and methods) for determining drought triggers and thresholds, while accounting for non-stationarity, will advance drought preparedness and prevent maladaptive response across regions and sectors. These improvements will also address variation among regions experiencing aridification versus those experiencing humidification, thus enabling appropriate drought risk thresholds and response priorities. Incorporating climate change data and impacts into drought indicators and conditions data provides a pathway for state, tribal, local, and sector-specific planning efforts to better prepare for future droughts on the basis of accurate climate conditions and future projections. All types of planning processes (hazard mitigation, land use, and water) at various scales will likely benefit from better drought assessment methods and a clearer understanding of how non-stationarity impacts drought risk and the associated cascading hazards. We acknowledge that improving both the data and the methods for determining drought response triggers and thresholds is necessary to adapt to climate non-stationarity.

3. Concluding Remarks

Non-stationarity complicates the interpretation of drought on the basis of drought indices and impacts. One of these complications is the reference period chosen to define and assess drought. Should drought be defined relative to the full period of record or a shorter reference period? The answer may not be categorical. We believe that multiple drought definitions or concepts are possible, and even needed, to correctly assess drought in a changing climate if assessment tools align with the definition or concept. The actions proposed in this perspective paper can help identify the correct tools and science that will allow for multiple drought definitions or concepts.

Choosing the most appropriate reference period requires the implantation of the following guidelines. First, the most informative baseline depends on the reason for the drought assessment (Lisonbee et al., 2024). We suggest that future research establish an explicit process (e.g., a decision tree) to help determine when to use a shorter reference period, when to use the full record, and when to use proxy data, such as modeled or paleoclimate data in the absence of sufficient observational data (e.g., Ault et al., 2014; Cook et al., 1999; Meko et al., 2007)—to assess the abnormality and seriousness of drought. It is considered best practice to include information about the selected reference period in all metadata, and include justification for the selected reference period in drought assessments, and drought and climate change research. We also recommend that weather and climate data providers establish systems that allow flexibility in accessing data of various or customizable baselines for calculating time series statistics.

Much work is needed before the scientific community has all the tools needed to adequately assess drought in a changing climate. Here, we have synthesized and prioritized 10 research questions or priority actions that, if addressed well, will likely have the most positive impact on advancing drought science in a non-stationary climate.

The top priority, reducing the sensitivity of drought indicators to non-stationarity, is essential for accurately assessing future drought impacts in the context of present or future climates. However, we acknowledge that the impacts of drought also are non-stationary, and we call on the research community to evaluate how and why drought impacts are changing. Many changes to drought dynamics and drought impacts are regional; we hope that more research will address regional differences in non-stationarity. Where the hydrologic cycle is expected to change in a warming climate (e.g., increased precipitation intensity with longer gaps between storms), we regard the use of precipitation effectiveness to capture water availability as more relevant for drought assessment. We encourage additional research that explores precipitation effectiveness and fill gaps in the current ability to apply this tool to drought assessment. Another step in advancing the science of drought assessment is understanding the physical drivers of drought and aridification and the interactions among them. Aridification can be exacerbated by land degradation, but efforts to conserve soil and improve soil health can limit negative impacts on food production and other ecosystem services. Furthermore, we call for improvements and guidance for drought planning, response, and adaptation. A uniform approach to drought planning methods is essential to address these challenges. This approach will require the use of accurate scientific data and be regionally appropriate for adapting to a changing climate. Finally, we urge collaboration among scientific disciplines to more holistically confront drought assessment in a non-stationary climate.

Data Availability Statement

Figure 1 was produced using randomized modeled data following the method outlined in Salles et al. (2019) adapted from the code available from https://github.com/eogasawara/TSED. Data sources for Figure 2 include Elephant Butte Reservoir Storage and 4-km monthly precipitation data. The reservoir storage data is U.S. Bureau of Reclamation data and is available from the USDA Natural Resource Conservation Service's National Water and Climate Center (https://wcc.sc.egov.usda.gov/reportGenerator/). The precipitation data is PRISM 4-km monthly precipitation data (PRISM Climate Group & Oregon State University, 2024) and is available from ClimateEngine.org (Climate Engine, 2024; Huntington et al., 2017) using the U.S. Hydrologic Unit Code 6 region boundaries for the Rio Grande Headwaters region. The maps in Figure 3 were created using PRISM 4-km monthly data (PRISM Climate Group & Oregon State University, 2024) which was obtained via

ClimateEngine.org (Climate Engine, 2024; Huntington et al., 2017). Maps from ClimateEngine.org are licensed under a Creative Commons CC-BY license (https://creativecommons.org/licenses/by/4.0/) and are used according to the license agreement at https://support.climateengine.org/article/111-license-and-citations. No adjustments were made to the maps, but the legends were enlarged for improved readability.

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