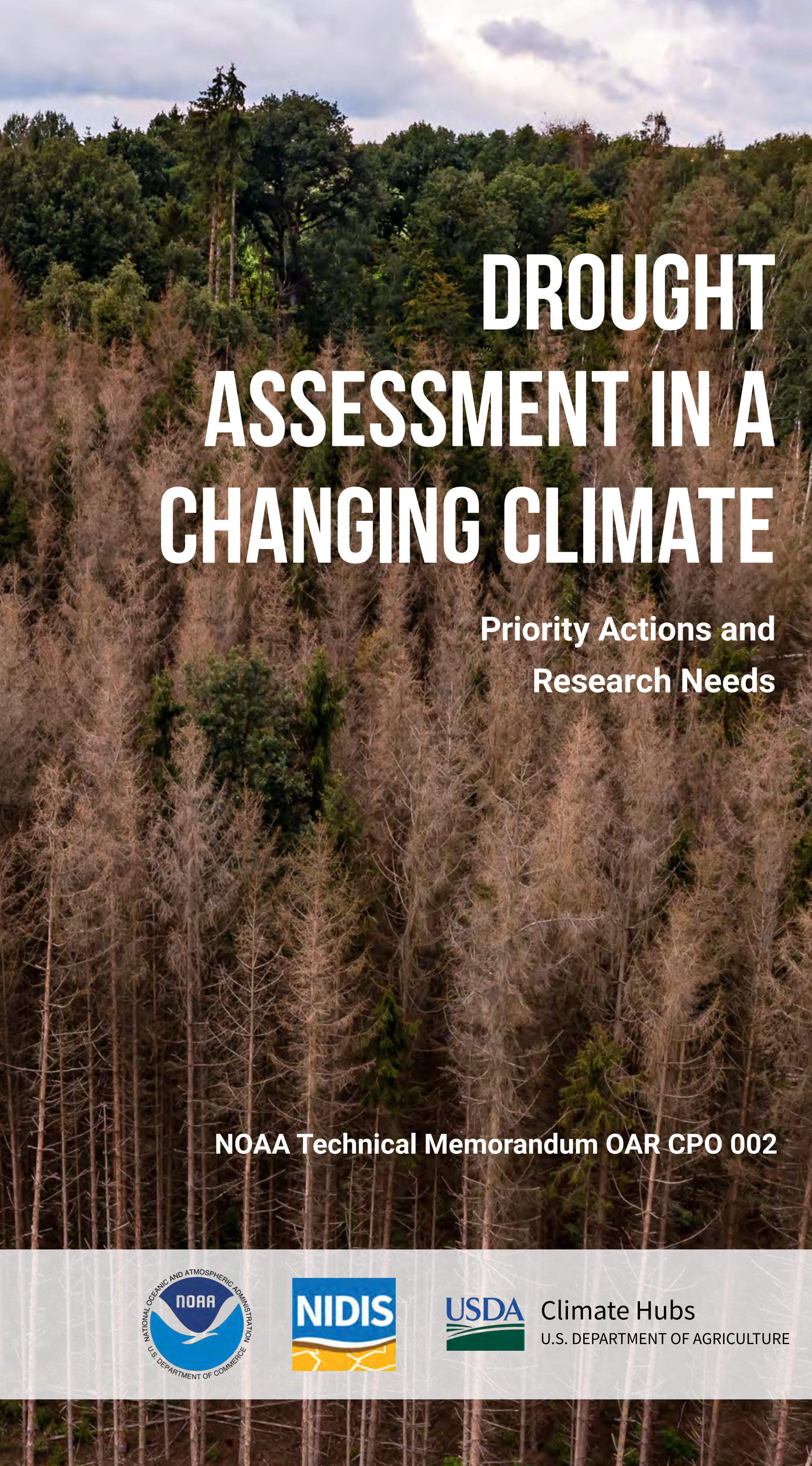

DROUGHT ASSESSMENT IN A CHANGING CLIMATE

Priority Actions and Research Needs

NOAA Technical Memorandum OAR CPO 002

NOAA NIDIS USDA Climate Hubs U.S. DEPARTMENT OF AGRICULTURE CIRES

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Drought Assessment in a Changing Climate: Priority Actions and Research Needs

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This report summarizes the ideas shared by the participants listed below at the technical working meeting as well as ideas contributed by reviewers. Drafting, coordinating review, and publication of the report was led by workshop planning team members Britt Parker, Joel Lisonbee, and Elizabeth Ossowski with support from Holly Prendeville and Dennis Todey. In addition to the many participants who provided feedback on this report, we would also like to thank technical experts from USDA, NOAA, and academic institutions who provided review of the report including Mark Brusberg, Jessica Halofsky, Bill Hohenstein, Ben Livneh, and Kristin VanderMolen.

The priority actions and research questions resulting from the workshop reflect the dialogue and discussion of its attendees, and do not represent official Administration policy or position, or an official policy or position of the individual organizations/agencies represented at the workshop.

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FOREWORD

NOAA's National Integrated Drought Information System (NIDIS) and USDA Climate Hubs are pleased to share with you *Drought Assessment in a Changing Climate: Priority Actions and Research Needs*, a report capturing the important contributions of partners across many agencies and institutions to address the challenge of assessing drought in a changing climate.

Today, the quality and quantity of water available for use by people and ecosystems across the country are being affected by climate change, increasing risks and costs across sectors. Variable precipitation and rising temperatures are intensifying droughts, reducing snowpack, and increasing heavy downpours. In 17 of the last 20 years (2004–2023), a drought event has qualified for NOAA's list of Billion Dollar Disasters (NOAA NCEI, 2023), and the total cost of these large drought events is estimated to be nearly $170 billion. This alone underscores why we must build our resiliency to these costly events. It also highlights why accurate assessments of current conditions must keep pace with the rapid change in our climate.

This report identifies some of the most pressing and strategic areas of research and action to advance the knowledge and understanding of drought assessment. We look forward to supporting the research and advancements needed to build more drought-resilient communities. Among the areas of research and action discussed in the report:

- Improved descriptions of how non-stationarity and low-frequency variability should shape our expectation for future water demands and drought frequency, intensity, and duration
- Improved understanding of how drought indicators relate to potential future impacts on the ground, especially across diverse communities and businesses and in the context of compounding or cascading climate hazards
- Improved understanding of the utility and application of drought assessments for decision making as they manage drought risks
- A holistic view of drought risk that combines physical information about water resources with an understanding of different communities' exposure and vulnerability

A non-stationary climate has broad implications for business as usual and risk management across the Nation. Communities and companies are increasingly realizing that climate change is happening, affecting them (economically, socially, ecologically), and happening at a more rapid pace. We hope that this report will guide researchers and practitioners as they work to better characterize, communicate, and manage our changing drought risks. Through this action, we can build a more resilient future.

Sarah Kapnick, PhD
CHIEF SCIENTIST, NOAA
NOVEMBER 2023

EXECUTIVE SUMMARY

Over the past few decades, significant advances have been made to improve the Nation's capacity to proactively manage drought risk by providing those affected with the best available information and resources to diagnose and quantify—or assess—drought conditions. Drought assessments can be a snapshot of present drought severity and extent, an analysis over time of drought duration, a retrospective look at the underlying drivers of a drought, an analysis of the impacts of drought on people or systems, or any other attempt to understand the dynamics of a particular drought. These assessments have a vital role to play in supporting communities in preparing for, mitigating, and responding to drought.

Improvements in data products, more accurate drought assessments, and investments in better coordination have served drought-prone communities well. Continuous integration of new needs and requirements from those communities is essential to maintaining the continuity of progress our country has already made. Today, the changing climate is causing the probability of extreme events to change, a phenomenon known statistically as non-stationarity. In the future, the intensity, duration, and frequency of droughts may change. This poses new challenges that are being raised by scientists, decision-makers, and practitioners. These challenges include the difficulty to distinguish natural variability, meaning the naturally occurring oscillations in the climate system, from forced trends, or the seemingly permanent changes caused by anthropogenic climate change. This also includes the complexity of understanding drought within socio-economic considerations and resource constraints (e.g., funding, capacity) that might limit the ability to integrate the latest science into operational data products.

Long-standing drought assessment challenges, including drought monitoring, observation, research, prediction, knowledge-sharing, and communication, are exacerbated by climate non-stationarity.

Drought assessment in a changing climate will require significant adjustments in approaches to address non-stationarity.

Around the country, those engaged in drought decision-making are considering a number of questions such as: Do current methods for assessing drought conditions consistently and deliberately consider non-stationarity? If not, could this result in a missed opportunity to promote drought planning and response strategies that build long-term community resilience and reduce risk? What research is needed to produce drought indicators that account for climate change? And what resources are available to support their development and integration into the current suite of indicators?

A technical meeting to discuss this issue was co-hosted by NOAA's National Integrated Drought Information System (NIDIS) and USDA Climate Hubs on February 28–March 1, 2023, where scientists, decision-makers, and practitioners were asked to address an overarching question: "What approaches should be taken to better incorporate non-stationarity into drought assessment?" Answering this question thoroughly demands thoughtful consideration of (1) the phenomenon of drought itself; (2) the experience of drought and its impacts; (3) the purpose of assessment of drought and its impacts; and (4) the preparation for and response to drought and its impacts, including actions to reduce impacts as well as policies and adaptation. Of these considerations, **the technical workshop focused largely on better understanding and assessing the *phenomenon itself*** by breaking the topic down into four sub-topics: (1) considering climate variability and drought assessment; (2) understanding drought in an aridifying (drier-trending) climate; (3) discerning drought in a humidifying (wetter-trending) climate; and (4) defining drought in terms of risk and likelihood of event.

This report captures the ideas and feedback of more than 100 subject matter experts from over 44 institutions across the drought research and practitioner communities who participated in the meeting and reviewed this report. The two-day meeting identified priority actions and outstanding research questions that would continue to advance drought assessment in a changing climate. From the large volume of input received at the meeting, ideas were collated and refined; however, they were not distilled down to a few top priorities, nor were ideas further fleshed out to incorporate a prescriptive scale for implementation. Instead, this report captures the breadth of feedback from the meeting itself.

In total, the report highlights priority actions and research questions across the following **fifteen focus areas to improve drought assessment by addressing gaps identified by the research and practitioner community**. These fifteen focus areas are presented individually with the acknowledgement that if they are approached as siloes, progress will be curtailed. Many are cross-cutting, progress in one will accelerate progress in another, and it is key that the drought community approach these issues collaboratively. Finally, while the primary focus of the technical working meeting was on better understanding and assessing the *phenomenon (of drought) itself*, focus areas on related planning, governance, and communication considerations are also critically important and were captured.

- Learning with Indigenous Communities
- Benchmarking our Understanding and Assessment of Drought in a Changing Climate
- Evaluating Data Relevance, Fidelity, Integration, Metadata and New Technologies
- Determining the Physical Drivers of Drought and How They Are Changing
- Understanding Drivers of Aridification and Their Interactions with Drought
- Addressing Regional Differences in Non-stationarity
- Improving Drought Indicator Performance
- Using Precipitation Effectiveness More Broadly to Capture Rainfall Variability
- Quantifying Water Demand in a Changing Climate
- Evaluating Drought Impacts and How They Are Changing
- Assessing Drought in Terms of Risk
- Assessing Policy through the Lens of Non-stationarity
- Strengthening Planning, Management, and Adaptation
- Improving Communication and Collaborative Knowledge Exchange

Across this discussion of diverse and important focus areas, chronic issues emerged that plague our Nation's efforts to adequately assess drought and its impacts, and these are exacerbated by climate change. These include gaps in drought monitoring and assessment and under-resourced observation and monitoring networks that require additional investment.

This report offers a rich collection of ideas for action and research that federal, tribal, state, local agencies and academic institutions can advance. Further prioritization and specification may be warranted to discern where limited resources might be most impactful, and this will be the focus of an accompanying synthesis paper for publication in 2024. Although the intent of the report is not to provide authoritative guidance or design specifications for specific research or programmatic endeavors, it is intended to illuminate current and future needs to best account for a changing climate in our drought assessment practices.

INTRODUCTION

Traditional drought assessment methods based on assumptions of a stationary climate may underestimate current and future drought risks, thereby posing challenges to agricultural producers, water managers, businesses, and decision-makers in planning and allocating resources effectively for a changing climate. Long-standing drought assessment challenges are exacerbated by climate non-stationarity, including drought monitoring, observation, research, prediction, knowledge-sharing, and communication. Drought assessment in a changing climate will require significant adjustments in approaches to address non-stationarity.

In this report, the term “non-stationarity” describes the statistical trend(s) that might be evident in a time series of any element, variable, or drought index as a consequence of anthropogenic climate change. Climate variability refers to the natural variability within the climate system and can range from very-long to very-short time scales. On very-long timescales, these may appear as trends within the climate system and might be hard to distinguish from anthropogenic climate change. We define *drought* as being temporary, stochastic and anomalous events (Appendix 1), even if those events last multiple decades (e.g., megadrought), while *aridification* describes a long-term change toward a permanently drier climate.

Drought assessment tools and other products such as the U.S. Drought Monitor, the U.S. Drought Portal, hydrologic models, and outlooks need to continually improve based on the latest science to better reflect fundamental differences between permanent change (e.g., trends towards wetter or drier) and temporary anomalies from normal conditions (drought). Drought assessment processes also need to improve such that they consistently and deliberately consider many factors in accounting for periods of record, drought type, impacts, regionality, and seasonality. In a non-stationary climate, these factors become even more salient. As such, data from across disciplines (e.g., health, social science) and knowledge systems need to be incorporated to improve assessments equitably. Extra consideration around drought assessment includes communication and planning implications. For instance, including climate change information in drought assessment might affect drought intensity characterization. These changes could impact disaster relief and adaptation programs and inform future policy.

There is an escalating demand for more research, information, and action to address the complications around drought assessment presented by a changing climate. Many aspects of the climate are different than even 30–40 years ago (Hayhoe et al., 2018). Improving the science that underpins drought assessment in a changing climate will lead to more accurate depictions of drought to provide better-informed decision-making. This report provides insights into the research agenda and investments to enable continued improvements in assessment processes, which are crucial for our Nation’s drought readiness in a changing climate.

STATE OF THE SCIENCE

Period of Reference and Normals in Drought Assessment[1]

According to the American Meteorological Society (AMS) Glossary of Meteorology, *drought* is defined as "a period of abnormally dry weather sufficiently long enough to cause a serious hydrological imbalance" (AMS, 2019a). Drought is a relative phenomenon in both space and time. To assess "abnormally dry weather," there needs to be a standard or reference of "normal" to act as a comparison. However, establishing what time period and spatial extent should be used to constitute "normal" is not straightforward. Climate change—be it externally (i.e., anthropogenically) or internally forced—provides that the past human experience is not always an indication of the future.

In 1935, the World Meteorological Organization began recommending a 30-year reference period for most climatological applications. However, extreme and exceptional drought is a relatively rare phenomenon. In order to capture enough drought events in a statistical sample, a common method has been to use as much data as possible, usually the full record of observed data. Many commonly used drought indices, when using a long record to represent a contemporary climate, do not account for measurable trends in the data. The practice of using all available data was first challenged by Landsberg (1975) and then again by Karl (1986) and Matalas (1997), approximately when climate change was beginning to become more mainstream in the scientific literature.

As a non-stationary climate has become more apparent, some research within the last decade has advocated for the use of shorter reference periods for drought assessment, with 30 years being the most commonly used. It has been shown that 30-year climatologies, when compared to longer stationary analyses, better reflect "current day" drought risk, provide greater standardization across datasets with differing periods of record, and account for climate change into the future (Hoylman et al., 2022). In addition to a call for a shorter reference period, some recent studies have taken this a step further by updating those reference periods more frequently to be representative of a contemporary climate (Cammalleri et al., 2021).

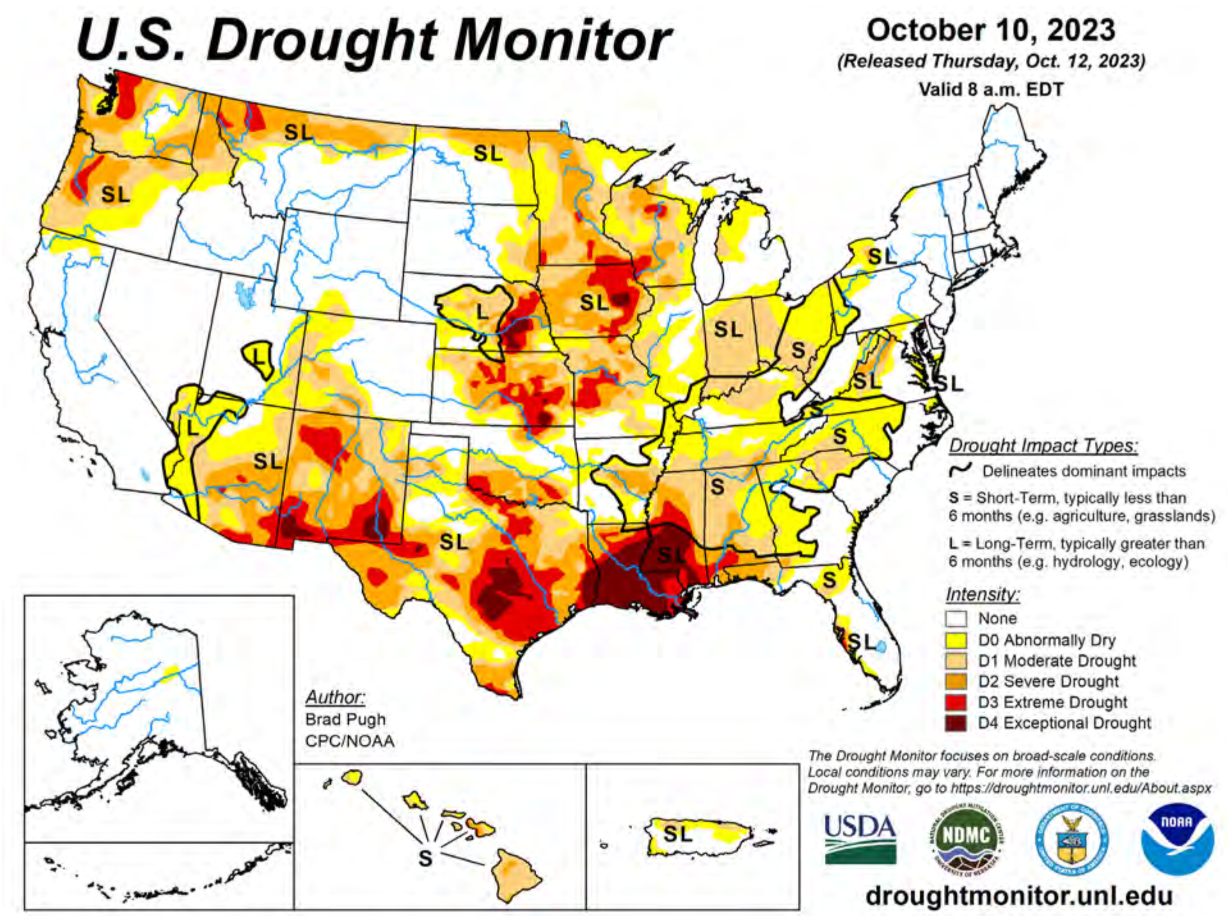
There are some downsides and precautions to using a shorter reference period. The severity of drought can change based on the reference period used (Karl, 1986; Paulo et al., 2016). For example, within the Western United States, the 30-year period from 1970-1999 was a relatively wet period, followed by 20 years that are now considered the worst megadrought in 1200 years (Williams et al., 2022). Using 1970-1999 as a baseline for drought assessment,

1 Excerpts from a literature review of climate reference periods for drought assessments is included in Appendix 3. This has been submitted for consideration in the Journal of Applied and Service Climatology. Once published it will provide historical context and academic guidance on how non-stationarity impacts drought assessments.

the decade from 2000–2010 would appear exceptionally dry, even though soil moisture during this time period was similar to decades like the 1930s and 1950s. The paleoclimate record in the Western United States suggests most 30-year periods would not capture the full range of variability in the region (Williams et al., 2022). Thus, for some purposes, a three-decade window would simply be too short to give actionable odds for wet/dry conditions.

This can become especially challenging when trying to separate climate variability from trends. To illustrate this point, consider a region where the paleoclimate record shows multidecadal droughts (i.e., “megadroughts”) were an occasional natural feature of the past. Now consider that the same region is also experiencing a well-established, anthropogenically forced trend. A climate reference period that incorporates the full modern record of approximately 140 years would still be too short to diagnose the very slow oscillations that might have caused the megadroughts of the past. Thus, if a megadrought develops again it will be very difficult to discern if drying is naturally driven and temporary in nature, or if the drying is externally-forced and permanent in nature. Therefore, if a trend is evident, then an attribution of that trend would be required to determine the best period of reference. Once the period of reference is determined, it and the underlying trend should be reassessed periodically.

Recent works have recommended other changes to how drought could be monitored and assessed because of climate change. These include research that has applied non-stationary statistics to the drought indices in a way that uses the full period of record but adjusts the index over time to account for a changing climate (e.g., Russo et al., 2013).



U.S. Drought Monitor from October 10, 2023. Source: National Drought Mitigation Center (NDMC) at the University of Nebraska-Lincoln, NOAA, and USDA.

National Drought Assessment

Many assessments of drought have been developed in the United States, including the long-standing USDM. Since 1999, the USDM has been a nationwide map issued every Thursday, showing the location, intensity, and duration of drought. The USDM is a joint product of the NDMC at the University of Nebraska-Lincoln, NOAA, and USDA.

The USDM ranks drought using a five-category classification system ranging from D0, representing "abnormally dry" conditions, a precursor to drought, to D4, exceptional drought conditions. The USDM is regularly used as a trigger for USDA drought-related programs and Internal Revenue Service tax deferral purposes (Stern & Lipiec, 2023; NDMC, 2023; Svoboda et al., 2022). The USDM incorporates multiple types of data at various timescales. The process of incorporating multiple data types is described as a "convergence of evidence" approach; an approach that has been continually refined over time. Today, the map's authors consider numerous indicators to produce the map, including drought impacts and local insight from over 450 expert observers around the country. This approach allows authors to assess severity of various drought types. The official process for analyzing data for the USDM does not constrain data to a specific reference period, but the USDM authors consider the period of record for each dataset when determining drought severity. The USDM process is a “data consumer” in that it uses data that are compiled and disseminated from many data providers. Some of these datasets have a relatively short record, such as the National Soil Moisture Network and satellite-derived drought metrics that have a record only as long as the satellite mission has been in place (often over 20 years, but sometimes as short as a few years). Conversely, some datasets have individual stations or recording points that potentially have over 100 years of record. The USDM process utilizes the results of drought index calculations and percentile rankings to compare across datasets and periods (Svoboda et al., 2002).

Non-stationarity and Drought Assessment Metrics

When trying to represent drought conditions in the current climate, using a full period of record and assuming stationarity in a dataset that has a clear trend will introduce bias (errors) into the drought assessment. Many common drought indices, such as the Standardized Precipitation Index (SPI; McKee et al., 1993), were originally based on the full period of record. This can be problematic when assessing drought conditions where there is a clear precipitation trend, as drought severity might be underrepresented in climates trending wetter and over-exaggerated in climates trending drier (Leasor et al., 2020; Hoylman et al., 2022; Sofia et al., 2023). This problem is clear when using a drought index that incorporates temperatures where there is a clear anthropogenic climate change signal. Thus, some researchers might choose to use a shorter reference period to be more representative of the present climate. The choice of a comparison reference period can change the assessed severity, duration, and extent of a drought, and therefore needs to be explicitly stated to allow for replicable science. Both approaches have pros and cons. The choice of which reference period used should be based on the underlying purpose of the drought assessment with research and user needs in mind.

The impacts of a non-stationary climate are playing out differently across the U.S. The Southwest, Midwest, and Northeast regions are experiencing a clear trend in regional climate that influences the values of a drought index, although not necessarily precipitation. The Southwest U.S. is not seeing a strong trend in annual precipitation over the full period of record (1895–2023), but rising temperatures and evaporation have led to more rapidly depleted soil moisture, runoff and streamflow in an already arid region (Overpeck & Udall, 2020; Mankin et al., 2021). As a result, episodic droughts feature higher temperatures than past droughts and are more impactful on the hydrology of the region, which is already stressed by human use (Gonzalez et al., 2018; Mankin et al., 2021). On the other hand, the Midwest and Northeast U.S. are trending wetter (Ford et al., 2021; Hoell et al., 2021) with more precipitation in the form of rain and less in the form of snow (Demaria et al., 2016). In the Midwest, this includes changes in the seasonality of the precipitation (Angel et al., 2018). This change in the underlying climate pattern also affects the way drought is manifested. Droughts in the Northeast tend to be of shorter duration than droughts of the past (Hayhoe et al., 2006; Xue & Ullrich, 2022), but potentially less frequent (Krakauer et al., 2019) and with a quicker onset (Yuan et al., 2023).

Shifts in Precipitation Variability

In addition to shifts in mean temperature and precipitation, changes in precipitation variability due to climate change are also complicating the way drought is assessed. Precipitation variability refers to the occurrence of extreme rainfall events, the number of heavy downpours over a short period compared to light rainfall over a longer period, and/or the time passed between rainfall events. Nationwide, there are trends toward increased heavy precipitation with longer gaps between precipitation events (e.g., for the Western United States see Zhang et al., 2021). Even in locations with no change in overall mean precipitation, more precipitation variability can reduce infiltration from a soil moisture or groundwater recharge perspective. Climate models have shown that this will likely provide more rainfall to surface runoff and less to soil moisture and groundwater recharge (Marvel et al., 2021) while increasing the amount of runoff entering rivers and streams (Scheff et al., 2022). Additionally, changing seasonal variability—as seen in increasingly wetter springs and drier summers for example—can present new impacts and challenges as well as exacerbate existing ones, including seasonal changes to the runoff ratio (runoff divided by precipitation; Scheff et al., 2022). Changing variability and seasonality require a diverse suite of indicators for monitoring, assessment, and prediction when diagnosing the severity or duration of a drought and in turn its impacts to different sectors.

Looking Beyond Precipitation

Looking beyond precipitation pattern changes, changes in water demand are also shaping drought assessment. When considering drought as an imbalance of supply and demand of surface moisture, then anything removing water from the system more quickly than it is replenished, whether natural or anthropogenic, can exacerbate drought.

One non-precipitation drought indicator that can change over time is the amount of water stored in large lakes. Large lake storage decreased over the past three decades due to both human and environmental factors (Wheeler et al., 2022; Yao et al., 2023). Human factors include increased water consumption and environmental factors include sedimentation creating storage losses in reservoirs, climate warming, and increasing evaporative demand.

Another non-precipitation drought indicator is evaporative demand. In a warming climate, increased evapotranspiration rates or atmospheric evaporative demand will increase the hydrologic imbalance. Actual evapotranspiration is different from evaporative demand, or potential evapotranspiration. As drought worsens, actual evapotranspiration initially rises with increasing evaporative demand, then falls as available soil moisture declines and water becomes limited. But potential evapotranspiration, the evaporative demand of the atmosphere, is energy-limited and will increase in response to increased temperature, wind, and sunlight regardless of available water.

Consider the example from Hobbins et al. (2019) when comparing changes in evaporative demand from an observed dataset from 1971–2000 with a modeled evaporative demand from 2051–2080. Hobbins et al. (2019) showed that evaporative demand over the Northern Plains might increase by about 1 mm per day, on average, from one period to the next. A similar analysis over the Four Corners region of the western U.S., where evaporative demand is already relatively high, shows a similar, but less pronounced signal (Hobbins et al., 2019). As a result of the increased evaporative demand in the Southwest, it is estimated that the Colorado River Basin will see a streamflow loss of about 9.3% per 1ºC of warming, driven by the compounding impacts of increased temperatures in the region (Udall & Overpeck, 2017; Hoerling et al., 2019; Milly & Dunne, 2020).

The impacts of increased evaporative demand on future hydrology are not always straightforward. Hobbins et al. (2019) show a link between higher evaporative demand and decreases in upper-level (top 10-cm) soil moisture, potentially reducing runoff and streamflow in the region, similar to what is estimated for the Colorado River. However, Scheff et al. (2021, 2022) points out that climate model simulations of future hydrology do not seem to consistently translate increased evaporative demand into drying soils or reduced streamflow. There are a number of reasons for this seeming discrepancy: upper level soil moisture changes experience higher variability and are more strongly influenced by evaporative demand at the surface than lower level soil moisture, and the models tend to increase vegetative response to rising CO_2. Both lower-layer soil moisture and increased surface vegetation will impact streamflow rates.

Changes in temperature and evaporative demand create added challenges when using drought indices that incorporate temperature and/or evaporation in their statistics, such as the Palmer Drought Severity Index (PDSI; Palmer, 1965) and the standardized precipitation evaporation index (SPEI; Vicente-Serrano et al., 2010). These drought indices would show a stronger trend in most regions when calibrated using a long historical record and would be useful for demonstrating a changing climate (e.g., Vicente-Serrano et al., 2010). However, these indices should be used with consideration and scientific guidance when assessing present day drought. Not all drought indices give temperature the same weighting and some may overemphasize the effects of temperature (Dewes et al., 2017). Furthermore, the calibration period used will impact the outcome of the drought assessment.

The choice of a drought definition and a comparison reference period can change the outcome of the assessed drought severity, duration, and extent (Seneviratne et al., 2012; Satoh et al., 2021). For example, where a strong precipitation trend is evident, the SPI using the full period of record will give a different drought severity than using the last 30 years as a reference period (Hoylman et al., 2022). Or, where a drought has been in place for less than a season, using a meteorological or agricultural drought index will provide a different drought severity than a hydrological drought index. Ultimately, the choice of which drought metrics and reference period used should be based on the specific research question and/or users' needs. The following questions could provide guidance: Why is the drought assessment being done in the first place? For whom? For what types of decisions? For where (which region/climate), and what are the observed trends in that place? Over what timescales? Is there physical evidence that can explain the statistical trend? The answer to these questions will determine the proper methodology for assessing the drought.

FOCUS AREAS FOR FUTURE INVESTMENT TO ADDRESS IDENTIFIED GAPS

This section contains priority actions and research questions identified through the technical workshop and organized around focus areas. Priority actions will improve our ability to assess drought in both the short- and long-term and apply to research, assistance, and management. Addressing these research questions will fill gaps in knowledge related to drought assessment in a changing climate and spur greater inquiry. These identified needs were not assigned to any one entity, given the depth and breadth of priority actions and research questions. Addressing these needs will require a whole-of-government and drought community approach.

14 FOCUS AREAS

- Learning with Indigenous Communities
- Benchmarking our Understanding and Assessment of Drought in a Changing Climate
- Evaluating Data Relevance, Fidelity, Integration, Metadata and New Technologies
- Determining the Physical Drivers of Drought and How They Are Changing
- Understanding Drivers of Aridification and Their Interactions with Drought
- Addressing Regional Differences in Non-stationarity
- Improving Drought Indicator Performance
- Using Precipitation Effectiveness More Broadly to Capture Rainfall Variability
- Quantifying Water Demand in a Changing Climate
- Evaluating Drought Impacts and How They Are Changing
- Assessing Drought in Terms of Risk
- Assessing Policy through the Lens of Non-stationarity
- Strengthening Planning, Management, and Adaptation
- Improving Communication and Collaborative Knowledge Exchange

LEARNING WITH INDIGENOUS COMMUNITIES

Indigenous Traditional Ecological Knowledge (ITEK) informs our understanding of climate change and environmental sustainability over time (Jantarasami et al., 2018). ITEK consists of the body of knowledge, beliefs, traditions, practices, institutions, and worldviews developed and sustained by indigenous communities in interaction with the biophysical environment (Toledo, 2002; Berkes, 1993). Integration of ITEK and western knowledge systems can be key to understanding and adapting to drought in a changing climate (e.g., Confederated Salish and Kootenai Climate Change Strategic Plan StoryMaps, 2023). Taking this a step further, actually co-creating knowledge creates an opportunity to look at questions differently, providing a historical context of change and adaptation learned throughout a long history of stewardship and an understanding of the interconnectivity and complexity of natural systems (Redsteer et al., 2015). This collaboration between western and traditional knowledge requires respect for tribal sovereignty, self-determination, and considerations of reciprocity when working with tribal nations and communities to build trusted relationships and partnerships (Bamford et al., 2020). Dialogue is also needed to consider and understand how to implement Free, Prior and Informed Consent as identified in the United Nations Declaration on the Rights of Indigenous Peoples (FAO et al., 2016). Learning with indigenous communities requires multidisciplinary approaches incorporating indigenous research methods, embracing different world views, and hybrid knowledge frameworks (Hoagland, 2016; Rai & Dhyani, 2023). Continued engagement with tribal nations and indigenous communities is imperative to improve drought assessment and build resilience in a changing climate, while fully reflecting the contribution of these partners (e.g., Dinan et al., 2022).

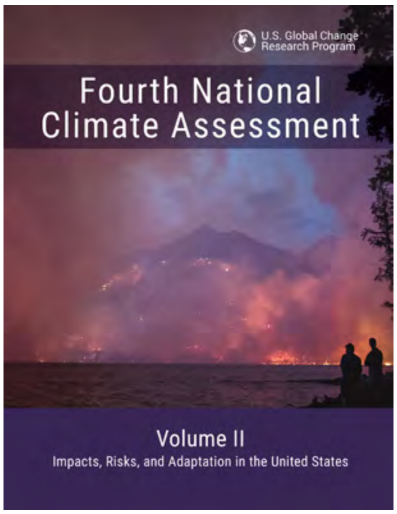
Bison Range on the Flathead Reservation, Western Montana. Photo by Crystal Stiles

Priority Actions:

1. Explore how ITEK can inform an understanding of risks and responses to drought, variability, forecasting onset and recovery of drought, and the likelihood, consequences, and impacts of drought.
2. Improve how drought risk is communicated and translated for people and places, and how risk is linked to their primary concerns and needs.
3. Build sustained relationships with entities such as Tribal Colleges and Universities to support things like maintenance of observation and monitoring networks while retaining technical knowledge within these communities and building capacity.
4. Ensure engagement is nested in reciprocity. Reciprocity is a native social norm that encourages a positive action to be rewarded with another positive action, motivating kind, respectful, and generous behavior (Bamford et al., 2020). Consider engagements that also honor indigenous customs and traditions (e.g., prayers, ceremony, offerings, gift exchanges).
5. Respecting data sovereignty requires that, as data such as oral histories are considered and integrated into assessments of drought, Memorandums of Understanding or other agreements are in place to ensure ownership and attribution of the information is acknowledged.

Bison Range on the Flathead Reservation, Western Montana. Photo by Crystal Stiles

BENCHMARKING OUR UNDERSTANDING AND ASSESSMENT OF DROUGHT IN A CHANGING CLIMATE



Cover of Fourth National Climate Assessment. Source: U.S. Global Change Research Program

Broadly, there is a need to benchmark our current understanding of drought in a changing climate. This would allow for more targeted research to build on the current state of science. It would include defining the drought-to-aridification continuum to help differentiate between drought, multi-decadal drought, and aridification. There are also efforts needed to improve drought assessment at a national level based on current best practices internationally to account for non-stationarity and increase national level coordination. The impacts of non-stationarity are a concern that is much broader than drought, and knowledge exchange across hazards and sectors could accelerate learning within and outside the drought community. To this end, improvements in drought assessment will have co-benefits in situations where drought is linked to other threats and hazards and where there are cascading impacts to communities (e.g., wildfire, debris flows, heatwaves/heat health, water quality). Interdisciplinary collaborations that approach the issue of drought assessment holistically, breaking down silos, will be key.

Priority Actions:

1. A National Academies (or similar) study is needed to benchmark our current understanding of drought in a changing climate. This study could approach the broader topic of drought and climate change. Key components of that study could focus on defining the drought-to-aridification continuum with the goal of developing a conceptual framework that can clearly differentiate between drought, multi-decadal drought, and aridification.
2. Convene an international learning exchange to share drought assessment methodologies that account for non-stationarity and best practices in drought assessment.
3. The National Climate Assessment (NCA) summarizes the impacts of climate change on the United States, now and in the future. Additional review and effort could help ensure that the non-stationary context of drought is treated consistently in the NCA, either with the addition of a chapter or through the regional chapters.
4. Drought is a hazard with economic impacts that match or exceed most other natural hazards. Consider investments that offer comprehensive coordination across federal

agencies to help communities reduce the impacts of drought. This is akin to a National Interagency Fire Center, the coordinating structure of Federal Emergency Management Agency's (FEMA) National Disaster Recovery Framework, or NOAA National Hurricane Center, or amplified messaging akin to National Hurricane Preparedness Month.

Research Questions:

1. What current methodologies used to assess drought at national or continental scales account for non-stationarity and how well do they work? What best practices can be shared to improve assessment globally?
2. How are other hazards addressing non-stationarity in assessments and monitoring impacts? Are there best practices that can be applied to drought assessment?
3. How can collection and understanding of impact data be used to improve drought assessment especially in terms of understanding the contribution of drought to cascading hazards?

HIGHLIGHT: OBSERVATION AND MONITORING

The words observation and monitoring are sometimes used synonymously when applied to drought assessment and diagnosis. However, these two terms have subtle, but meaningful, differences. The word observation often describes the action or process of measuring or recording something to collect data about it, such as a rainfall observation. The word monitoring often describes observing the progress or impacts of the drought over time. These uses are in line with the Merriam-Webster definition for observation: "an act of recognizing and noting a fact or occurrence often involving measurement with instruments", and for monitor: "to watch, keep track of, or check usually for a special purpose". For drought, we observe and monitor the environment and the impacts of drought.

Environmental observations can be derived from many sources. *In situ* measurements are gleaned from observation networks such as:

- State mesonets
- U.S. Geological Survey (USGS) Groundwater and Streamflow Information Program (GWSIP)
- Natural Resources Conservation Service (NRCS) Snow Survey (SNOTEL)
- Remote Automatic Weather Station (RAWS) networks
- Climate Reference Network (USCRN)

Observations are also collected through citizen science efforts, like:

- NOAA's Cooperative Observer Program (COOP)
- Community Collaborative Rain, Hail and Snow Network (CoCoRHaS)
- Local Environmental Observer Network (LEO)

Remotely sensed data are taken from radar and satellite products. A few of these include:

- Moderate Resolution Imaging Spectroradiometer (MODIS), Gravity Recovery and Climate Experiment (GRACE), Integrated Multi-satellitE Retrievals for GPM (IMERG), and Soil Moisture Active Passive (SMAP) from NASA
- Normalized Difference Vegetation Index (NDVI) and the Evaporative Stress Index (ESI) from the Geostationary Operational Environmental Satellite (GOES) ET and Drought (GET-D) product system from the NOAA National Environmental Satellite Data and Information Service (NESDIS) Center for Satellite Applications and Research (STAR)
- Crop Condition and Soil Moisture Analytics Tool (Crop-CASMA) from USDA
- Products from various other data providers.

Satellite and radar observations are also used to support modeled analyses, such as from NASA Short-term Prediction and Transition Center – Land Information System (SPoRT-LIS), which assimilates these remotely sensed data to produce soil moisture analysis.

In addition to measuring environmental changes, these data (*in situ* and remote-sensed) can support the inference of drought impacts. Satellite products can remotely observe vegetation health, which can indicate drought stress. Hydrologic measurements can indicate available soil moisture and reservoir storage which can also imply drought stress when these are low. Some of these inferences can be verified using volunteer impact reports such as from the Condition Monitoring Observer Reports (CMOR) system, as well as some of the previously mentioned citizen science programs. These conditions reports provide valuable intelligence on drought impacts and local conditions as a drought develops, worsens, or improves.

Despite the wealth of observation and monitoring, wide gaps remain. Spatial and temporal gaps exist in all surface observation networks. Satellite-derived data can have coarse spatial resolution, data latency, or verification/ground truthing challenges. Impact reports rely on willing volunteers to submit their reports, and many socioeconomic impacts are not reported.

CoCoRaHS rain gauge before a storm. Photo by Henry Reges/CoCoRaHS HQ

A mesonet station from the Montana Mesonet on the Confederated Salish and Kootenai Tribes Bison Range. Photo by Britt Parker

EVALUATING DATA RELEVANCE, FIDELITY, INTEGRATION, METADATA AND NEW TECHNOLOGIES

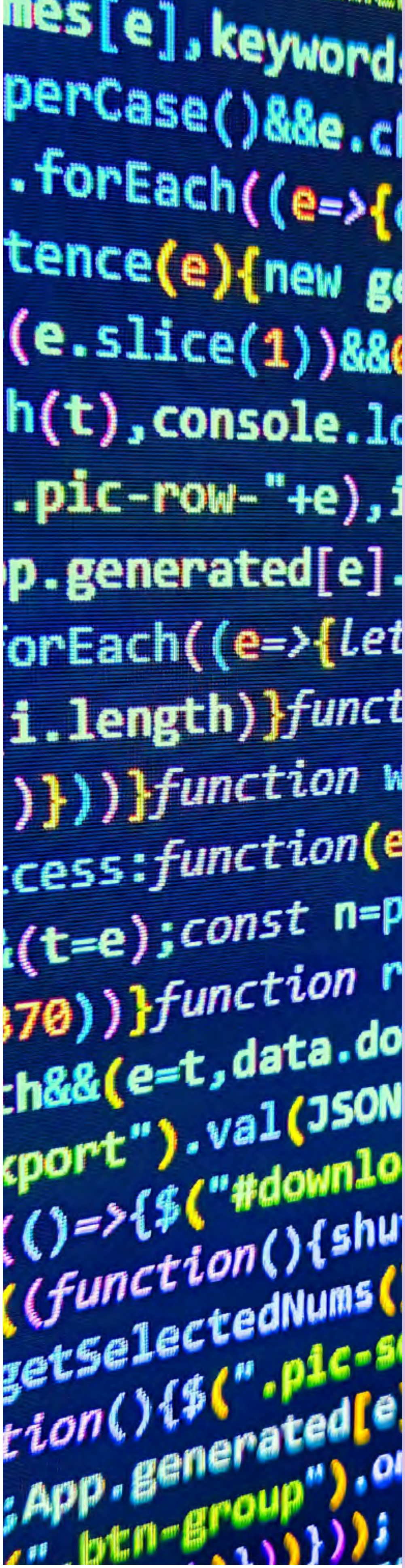
Drought assessments use a variety of *in situ*, modeled, and remote data sources and products. The quality and relevance of these datasets needs to be consistently evaluated for efficacy in characterizing drought in a changing climate. A clearinghouse to verify performance for new and commonly used metrics and indices would greatly benefit scientists and climate service providers. A scientific board could convene to provide guidance and research results to climate service providers who currently disseminate various drought information. The accuracy, completeness, consistency, and timeliness of data—data fidelity—will continue to be important in a changing climate. Careful consideration should be made to streamline, integrate, and, in some instances, consolidate or discontinue existing data products and services, before or alongside the development of new products. This is especially important as new technologies in data science, artificial intelligence, and soft computing create previously unavailable capabilities in leveraging data for improved design, understanding, prediction, and communication of environmental data and the systems used to collect them. Examples of applying these new technologies include using:

- *fuzzy inference systems* for characterizing water availability in a way that is holistic, quantitative, and objective while integrating experiential (e.g., expert and stakeholder) knowledge (Fleming et al., 2014);
- *information theory* and complex *network theory* for improving and rationalizing the design of environmental monitoring networks (e.g., Caselton & Husain, 1980; Halverson & Fleming, 2015); and,
- *artificial intelligence* applications relevant to environmental science and climate hazards.

There is the potential for these new technologies (e.g., artificial intelligence, soft computing) to enhance overall relevance of various datasets used in drought assessment. However, efforts are needed to increase the transparency and explainability of these new technologies, improve understanding of these technologies and their appropriate use for environmental and water resource communities, and build systems specifically suited for practical operational applications (e.g., McGovern et al., 2019; Kratzert et al., 2018; Fleming et al., 2021a,b).

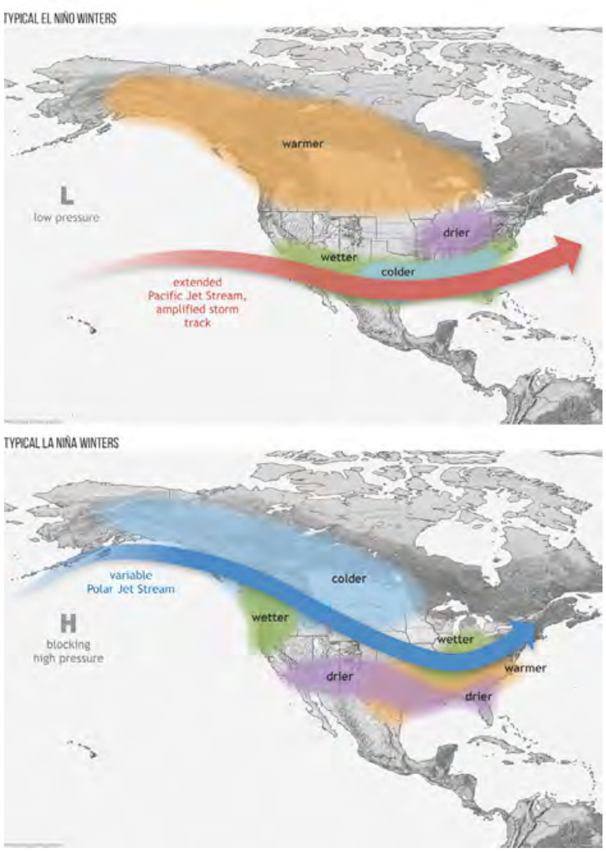
Priority Actions:

1. Characterize drought at seasonal, monthly, daily, and sub-daily time scales to connect drought indicators with impacts in real-time to inform the scale and pace of response and adaptation.
2. Develop a consistent metadata framework for drought metrics. Within the framework, metadata should include period of reference given the sensitivity of drought metrics to length-of-record or truncated reference period.
3. Ensure complete metadata includes data reuse restrictions and ownership to ensure proper attribution when considering the integration of ITEK and other knowledge systems into drought assessment.
4. Integrate information from several different data sources and platforms to contextualize drought by offering different, yet well documented, temporal and spatial perspectives to changing conditions. This will allow observations and assessment to be packaged in a way that communicates the condition, impact, and consequence to inform the appropriate response.
5. Explore new data science and soft computing technologies and their appropriate and transparent uses for practical operational applications to improve environmental and resource management.



DETERMINING THE PHYSICAL DRIVERS OF DROUGHT AND HOW THEY ARE CHANGING

Drought drivers include climate dynamics that can create persistent weather patterns, which can cause droughts to form or end. The El Niño–Southern Oscillation (ENSO) is perhaps the most commonly used climate driver for drought prediction. Anthropogenic climate change might result in changes to the way ENSO impacts drought development and demise, although the details of those changes remain uncertain (Power & Smith, 2007; Cai et al., 2020). Other climate drivers, such as land-atmosphere feedbacks (Miralles et al., 2018), the Pacific Decadal Oscillation (PDO), the Atlantic Multi-decadal Oscillation (AMO), and the Indian Ocean Dipole (IOD), also influence drought progression across North America, but like ENSO, the influence of these drivers in a warmer world is uncertain (Pu et al., 2016). Despite the uncertainty, natural variability will continue to contribute to droughts and seasonal-to-decadal precipitation trends (sometimes wetter and sometimes drier).



El Niño and La Niña winter impacts on North American winters. Source: NOAA's Climate.gov

When multiple, slow-moving patterns are evident in the climate system, they can amplify or dampen alternate climate patterns, creating non-linear behavior in drought response. This climate variability, in tandem with underlying climate trends, can create unprecedented climate extremes. Novel drought conditions are emerging, creating droughts that look different today than they did a generation ago. Examples include "hotter" droughts and larger vapor pressure deficits (Mankin et al., 2021), human-induced and human-modified droughts (e.g., Crausbay et al., 2020), flash drought (Yuan et al., 2023; Christian et al., 2023), and increasing snow drought (Marshall et al., 2019) in a warmer climate. Drought forecasters can use seasonal forecasts to interpret and predict the influence of multiple climate drivers on temperature and precipitation patterns. However, seasonal precipitation forecasts over parts of the U.S. (especially the western U.S.) lack forecast skill (Pan et al., 2019; Kumar & Chen, 2020).

Improved modeling can increase understanding of drought's drivers. Modernization of models to better represent land surface processes (e.g., evapotranspiration, soil moisture) and ensuring the correct representation of global-scale drivers (e.g., the tropical Pacific) can improve our understanding of drought indicators and prediction at sub-seasonal to seasonal timescales. Deeper understanding of climate drivers can come from using machine learning techniques, improving representation of these processes and interactions in numerical models, and improving global observations/diagnostics to reliably attribute climate drivers.

Priority Actions:

1. Evaluate and enhance modeling to better represent processes at the land surface (e.g., evapotranspiration, infiltration) and other drivers (e.g., ENSO, localized land–atmosphere feedback) to improve drought indicators and prediction in areas where precipitation patterns are changing.
2. Improve understanding of how rising temperatures interact with other climatic factors to influence drought to include whether these relationships are stable in a changing climate, and if not, how they are projected to change.
3. Investigate the expectations of megadrought in the future being driven largely by persistent warming trends instead of low-frequency climate variability, taking into account the paleoclimate evidence for large-scale climate oscillations driving megadrought (Coats et al., 2015, 2016; Steiger et al., 2019)[2].
4. Evaluate and synthesize mechanisms leading to warmer droughts given that they are expected to have greater effects on soil moisture, water availability, plant mortality, and wildlife.
5. Continue to explore and evaluate the use of remote sensing as a viable path in hydro-climate applications and modeling, particularly as satellite records get longer and their integration with models becomes more commonplace.

Research Questions:

1. What are the effects of greenhouse gas emissions on low-frequency climate variability (e.g., ENSO, PDO, AMO) as it relates to drought (Rashid & Beecham, 2019; Geng et al., 2022; Fix et al., 2022)?
2. What physical drivers contribute to multi-year drought? How are those drivers changing? Is this a way that non-stationarity is impacting the characteristics of a drought event?
3. What is the role of temperature in a changing water cycle as it relates to drought? How does temperature affect drought during different seasons? Does a changing baseline mean that it is getting harder to get out of drought?
4. How accurately do climate-based drought indices (e.g., PDSI, SPI, SPEI) represent land- and water-based drought features and processes (e.g., streamflow, groundwater, soil moisture, vegetation)?

2 Some priority actions from the workshop were given with citations while most were not. Where a citation was provided, we are including those with the priority action.

5. How well do global and regional climate models simulate non-stationarity in drought, including the effects of global and local drivers of non-stationarity as distinguished from natural variability?
6. When considering climate drivers, how does monitoring and modeling uncertainty limit and/or impact our ability to disentangle drought from aridification?

(Top left) Albuquerque, New Mexico, Sept. 27, 2023. A distant thunderstorm. Photo by Joel Lisonbee; (Top right) Lake Granby, Colorado, June 16, 2023. Pinyon Pine after a rainstorm. Photo by Joel Lisonbee; (Bottom) Albuquerque, New Mexico, Sept 27, 2023. Prickly Pear. Photo by Joel Lisonbee

UNDERSTANDING DRIVERS OF ARIDIFICATION AND THEIR INTERACTIONS WITH DROUGHT

What is the difference between a very long drought (multiple decades) and a permanent change toward a more arid climate? There is a fundamental need for a unified framework to define, identify, and quantify the drought-to-aridification continuum. As simple as this might seem, there is no broad consensus on what constitutes drought in a changing climate, nor how to distinguish the relative contributions of drought and aridification across the dryness spectrum. Furthermore, in regions where droughts commonly last for several years and can occasionally last for decades, how can a very-long drought be distinguished from a permanent change?

Furthermore, uncertainty measurements are seldom incorporated into drought assessment frameworks, but are critical for better depictions of drought. Addressing this problem requires a process-level understanding of the links between aridification and drought, from the complex interactions involving snowpack, land surface properties, vegetation, and river flow, to the impacts of anthropogenic forcing and the variability on multi-decadal timescales that can arise naturally within the climate system.

Aridification could be considered a regional manifestation of climate change towards warmer and/or drier conditions. Understanding this phenomenon relative to natural variability has a range of implications for practices within the resource management community. For example, understanding aridification versus drought can inform which periods of record are most relevant for activities ranging from long-term resource planning to short-term model calibration. This would clarify the nuance between sporadic drought, multi-year drought, multi-decadal drought (i.e., megadrought), aridification, and other drought-related terminology as decision-makers pursue acute response actions and longer-term strategies. Understanding the origins of aridification and its impact on drought is key to informing short-term risk management and long-term adaptation.

Priority Actions:

1. There is a fundamental need for 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.

Research Questions:

1. What are the drivers of regional aridification—anthropogenic vs. natural, predictable vs. unpredictable—and how does aridity influence drought characteristics (e.g., onset, recovery, frequency)?
2. How do anthropogenic forcings impact soil moisture, snowpack and snowmelt, plant physiology, and wildfire linkages with drought?
3. How does aridification interact with droughts? Will aridification increase serial droughts and pan-continental droughts in addition to increasing intensity and frequency of individual droughts?
4. Will the interaction between aridification and drought lead to abrupt changes or tipping points in drought and aridity regimes?
5. Can research on regional hydroclimate attribution science be employed to better differentiate persistent drought from aridification and improve predictability?
6. How do different climate drivers influence both drought and aridity and how do those drivers influence drought demise but not aridity?

ADDRESSING REGIONAL DIFFERENCES IN NON-STATIONARITY

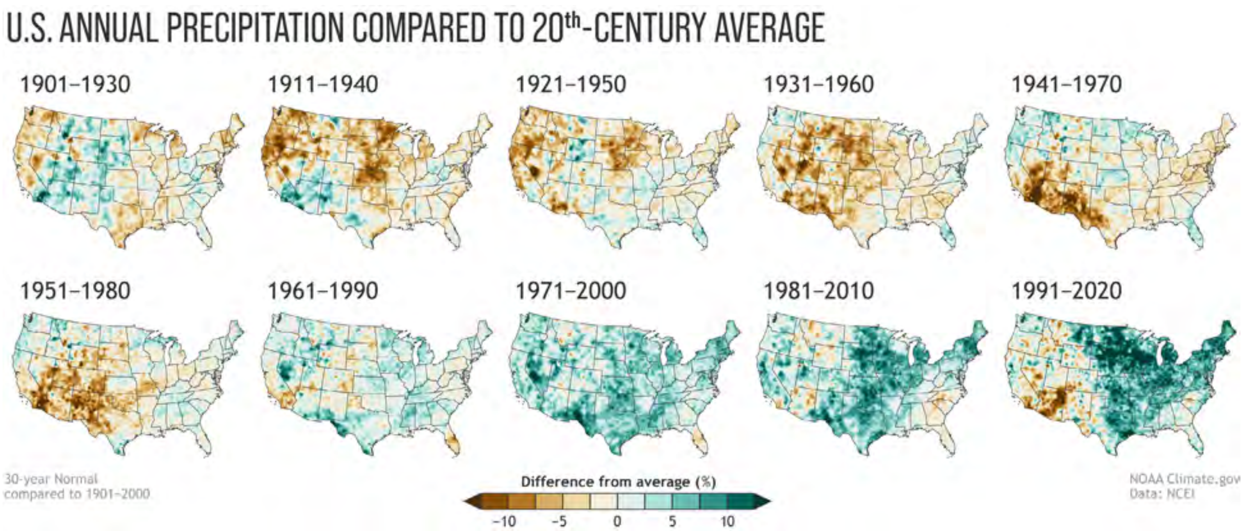
Climate change manifests differently across space and time and affects different regions in unequal ways. Two opposite examples in the United States are the Southwest, which is trending warmer and drier, and the Northeast, which is trending warmer and wetter. When assessing national trends, these two regional trends counter each other. Another example is when the Northern Plains states are grouped together to look at long-term trends. Since the early 20th century, the Eastern Plains (i.e., the Dakotas) have become wetter, while the Western Plains (i.e., Montana and Wyoming) have become drier. When looking at the Northern Plains as a combined region, these two different trends are diluted (Easterling et al., 2017). There needs to be an acknowledgement and systematic accounting for regional to sub-regional differences in non-stationarity when applying drought indicators and assessing drought and drought impacts. Climate change might affect current drought indices in similar or different ways, requiring better scientific understanding of spatial-temporal sensitivities. Defining the regions[3] at which drought is monitored and assessed is critical to account for the unique physical and climatological attributes of different parts of the United States. Regionalization requires an understanding of the interplay between indicators, where some might be more dominant by location and/or season, especially under climate change, and how indicators could be weighted to improve drought assessment. Regionalization also addresses the challenge that economic sectors, cultural practices, ecosystems, and habitats differ from region to region, and therefore experience different drought impacts.

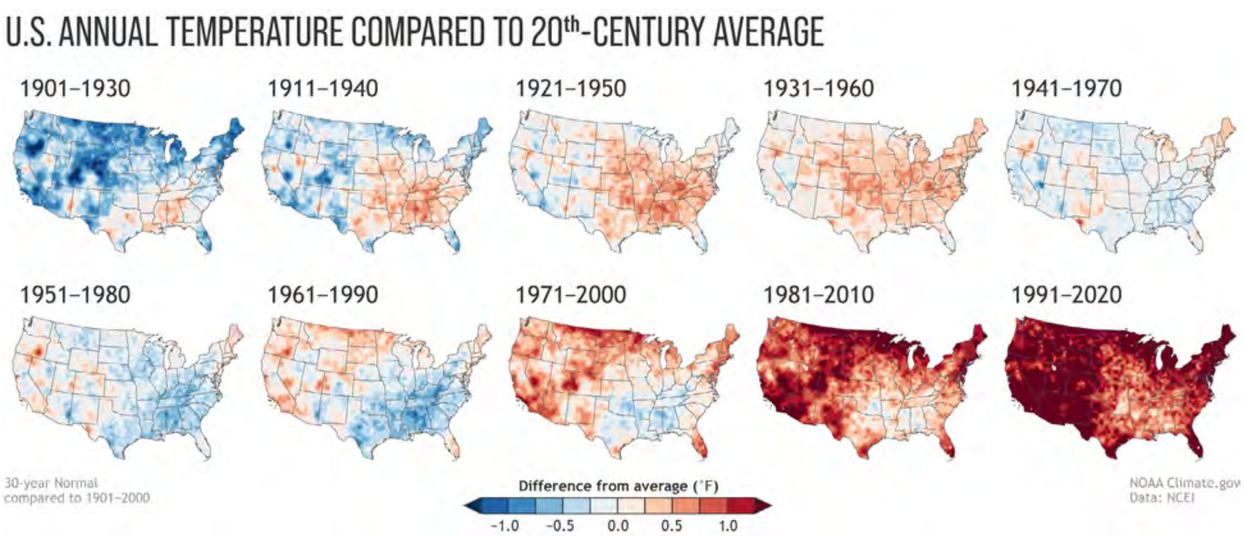
Priority Actions:

1. Expand on current efforts to develop drought assessment scales from global to continental to regional, acknowledging the pros and cons of each scale of assessment and the needs to fully fund these efforts.
2. Evaluate and compare current drought indicators to determine if they depict drought conditions appropriately and effectively given non-stationarity. Also, identify what indicators are most applicable at the regional scale, while also recognizing that these regions might also be responding to climate change in unique ways.
3. Synthesize research on existing and emerging issues and/or weaknesses in current means of drought assessment by region, as it pertains to non-stationarity.

3 “Regional” should be defined based on the requirements of the assessment. These can include: climate divisions, watersheds, states, eco-regions, agricultural systems or any other area—of various sizes—with shared attributes.

4. Represent and clearly communicate uncertainty and/or confidence in drought assessment to inform the application of the information in regional decision-making. Recognize regional differences in drought and non-stationarity, consider expanding the incorporation of regional information into national drought assessment products.
5. Develop and strengthen partnerships with regional and local communities and drought experts to ensure regional differences (including differences in resource allocation) are well understood and considered in state and federal assessment.





U.S. Annual Temperature and Precipitation Compared to 20th Century Average. Source: NOAA's Climate.gov/National Centers for Environmental Information (NCEI)

Research Questions:

1. How can a drought index/drought category be contextualized to account for large-scale climate oscillations (Jiang et al., 2019) relevant to various regions?
2. What are the optimal time scales to calculate percentiles or standardized anomalies for application in drought indices?
3. What is the climate sensitivity of drought categories to the period of record by region?
4. How sensitive are drought metric percentiles to period of record and approach (e.g., moving window, quantile regression approach, general additive model with time, general additive models with time and climate teleconnections) and drought type (i.e., as was done for flooding in Jain & Lall, 2001)?
5. What are the regional and sub-regional characteristics of non-stationarity, and how can these be used to understand the nature of droughts and other extreme events?
6. How is regional variability of drought indicators changing over time and with climate change?
7. How does changing variability affect the indicator-impact relationship in each region?

IMPROVING DROUGHT INDICATOR PERFORMANCE

Recent research has shown drought metrics are sensitive to climate change and non-stationarity (e.g., Hoylman et al., 2022; Stevenson et al., 2022; Sofia et al., 2023). More specifically, drought metrics and models are very sensitive to the reference period chosen to assess current conditions. Non-stationary drought metrics and models are available and often characterize non-linear trends in meteorological time-series (e.g., Generalized Additive Model in Location, Scale and Shape modeling; Wang et al., 2015; Rashid & Beecham, 2019). These methods attempt to capture changes to the central tendency and variance in the meteorological time series and account for these changes over time. Methods such as these might be preferable, as they can consider past extreme events (e.g., the Dust Bowl) in the characterization of current events, while also leveraging information about more recent climatological conditions. However, there might be some drawbacks to these methods in that some are complex and might not be easily applied to operational drought monitoring systems or might need to be accompanied by effective communications (Cammalleri et al., 2021). In addition to drought metrics that use the full period of record while statistically accounting for non-stationarity, recent research has proposed maintaining the raw dataset but truncating it to only include the most recent past. This framework follows the notion of climate normals as established by the World Meteorological Organization. However, depending on the rate of change at a location, shorter or longer reference periods with annual updates are preferable.

There are other challenges that also impact drought indicator performance to include changes in extreme events, changes to snowpack and melt, as well as understanding drought recovery. This section provides priority actions to work toward more sophisticated approaches to incorporate non-stationarity statistics in drought metrics and assessments. This could include exploring new approaches or modifying existing ones. As more sophisticated approaches are validated and incorporated into drought assessment, the community can consider retiring older methods or metrics that are no longer useful.

Priority Actions:

1. Conduct a Drought Indicator Intercomparison Project to include the creation of a centralized function (e.g., OpenET, World Climate Research Programme Coupled Model Intercomparison Project, Agricultural Model Intercomparison and Improvement Project) for comparing drought metric efficacy in terms of decision-making (e.g., for versions of SPEI calculated differently, such as Thornwaithe or Penman-Monteith or Penman PET equations, or with different periods of reference). Provide guidance on when they should be used, and at what time, location, or in an ensemble. Results could be used to update the WMO Handbook of Drought Indicators and Indices.

2. Develop guidance as to which climate reference periods are most appropriate for various applications, including the drought assessment process. Specific considerations include: across drought indices, for datasets with short periods of record, regional differences, and when comparing multiple indices of various record lengths.
3. Evaluate current monitoring infrastructure to ensure data are available to improve performance of existing and future indicators given non-stationarity.
4. Conduct a literature review and summarize with practitioners the existing knowledge on drought assessment metrics and tools that are sensitive to changing climates and non-stationarity.
5. Distinguish between drought and aridification and develop and operationally adopt distinct environmental indices for these two conditions.
6. Evaluate the performance of current drought indices to account for runoff and infiltration during high intensity precipitation events and consider these findings in drought assessments.
7. Develop or improve drought indicators that realistically handle variability of precipitation at a shorter temporal resolution (e.g., sub-monthly or sub-daily) to account for sporadic, intermittent, or extreme rainfall.
8. Deliberately account for changes in seasonality, intensity, and interannual variability of precipitation in drought assessments.
9. Evaluate methods for improving indicator performance in locations where indicators are complicated by climate change. For example, in Alaska, where drought is not well understood, the warming climate is leading to increases in streamflow and soil moisture due to thawing permafrost and melting glaciers, even during periods of below-normal precipitation.
10. Develop or improve existing drought recovery products that include temperature and other atmospheric measurements, snowpack, shallow groundwater, and other drought metrics, and evaluate their efficacy. Ensure products capture “drought buster” events, the role of non-stationarity, and nuances such as reservoirs or groundwater.

Research Questions:

1. How can observations and models be used and combined to define and quantify non-stationarity?
2. How accurately do current drought metrics capture changes in variability?
3. How can non-stationarity be addressed while adequately sampling the full range of drought variability? What existing or new methods can address non-stationarity?
4. How sensitive are drought metric percentiles to period of record and approach (e.g., moving window, quantile regression approach, general additive model with time, general additive models with time and climate teleconnections) and drought type (i.e., as was done for flooding in Jain & Lall, 2001)?

5. Drought is defined by not only lack of precipitation, but also other indicators (e.g., evaporative demand, vegetation changes), (1) how are these changing over time, and (2) are they reliable indicators for drought? In evaluating the reliability of current indicators or future indicators, consider using impact data in the evaluation methodology.
6. What are the right indicators to track intense precipitation events through time? Would a weighted SPI work? What are other variables (beyond SPI) that would be more informative, whether on their own or in combination with SPI?
7. What methods have been used, and what new methods could be considered to determine the utility and relevance of particular drought indices (e.g., snowpack) in a changing climate?
8. Determine how changing variability affects the indicator-impact relationship in each region through an evaluation of the indicators and how future conditions will impact their uses.
9. What reference frame (e.g., reference period, experience) is most appropriate for describing drought within aridifying and humidifying climates? Does the choice of framing vary with definition of drought, sector, or decision served?
10. Which indicators are useful/valuable to each sector or community in areas experiencing aridification? Are the indicators effective in informing management decisions and adaptation?
11. How are low-frequency, high-intensity precipitation events reflected in variables and drought indices, and how do they impact drought assessment temporally and spatially?
12. How can drought indices better reflect how intensity of an event affects drought conditions? Are there times (and if so, when) current drought indices should be forgone in the event of high-intensity precipitation events because they will not represent the condition on the ground well?
13. What constitutes drought recovery? What are the most appropriate drought metrics and spatial and temporal scales to look at for drought recovery? How do high precipitation events, or series of events (e.g., atmospheric rivers), contribute to recovery?
14. How have drought intensification rates (and recoveries) changed during the past few decades? How could they change in the future based on model projections?
15. Can sector and region-specific user-defined drought indicators be developed, and if efficacious, be incorporated into national drought assessment products?
16. How are drought metrics related to primary productivity in different ecological or agricultural systems? Are there benchmarks that can be associated with suggested actions?

HIGHLIGHT: FLASH DROUGHT

Flash droughts are droughts characterized by unusually rapid intensification (Otkin et al., 2022). There has been a transition toward more flash droughts over 74% of global regions during the past 64 years (Yuan et al., 2023; Christian et al., 2023). Further, this transition is associated with greater evapotranspiration and precipitation deficits caused by anthropogenic climate change and is projected to expand to all land areas in the future. Flash drought increases the complexity of drought monitoring and forecasting, making the priority actions and research questions associated with this phenomenon even more important in our quest to improve drought assessment in a changing climate.

Pictures showing the diverse impacts of flash drought during 2021, including (a) spring wheat in central Montana that did not have enough rain to germinate by 9 Aug, (b) heavily grazed pasture in central Montana on 7 Sep, (c) poor winter wheat heading in southeastern Washington on 21 May, and (d) a grassfire in central South Dakota on 2 Aug. All pictures were obtained from the Condition Monitoring Observer Report for Drought (CMOR-Drought) tool maintained by the National Drought Mitigation Center. Citation: Bulletin of the American Meteorological Society 103, 10; 10.1175/BAMS-D-21-0288.1

USING PRECIPITATION EFFECTIVENESS MORE BROADLY TO CAPTURE RAINFALL VARIABILITY

Shifting precipitation patterns due to climate change can be quantified in a number of different ways. In addition to trends in monthly or annual precipitation totals, trends in the intensity, duration, frequency, or extent of precipitation events can be evaluated. An example of this challenge for drought assessment is when monthly precipitation totals are near or above normal, but that precipitation falls in only a few short events. In cases like this, much of the precipitation typically runs off, with little infiltration into the soil.

Most common drought indices are ineffective at capturing the variable nature of precipitation (e.g., extreme events), which can influence the availability of water at a daily timescale. For example, the SPI and the SPEI metrics consolidate daily precipitation measurements into longer-periods (e.g., 30-days, 60-days), making the user unaware if the precipitation came in several small events or one large one.

The term *effective precipitation* was introduced by Byun and Wilhite (1999) to describe a daily sum of precipitation with a time-dependent reduction function to represent the daily depletion of water resources. Effective precipitation is meant to represent the water that remains in the landscape after accounting for runoff and evaporation. Scheff et al. (2022) points to the concept of a runoff ratio and indicates that rainfall events that might be ineffective at soil infiltration might be highly effective at increasing streamflow and reservoir storage. Key components to assess effective precipitation, whether for runoff or infiltration, include runoff, evapotranspiration, and soil moisture and groundwater. While this concept could prove quite useful in evaluating changes in soil-water availability, it has its shortcomings and challenges. These include the lack of agreement on a definition, difficulty accurately calculating the depletion of water resources in nature by runoff and evapotranspiration, and the inability to apply a general methodology on a large geographic scope. Further exploration follows.

Definition Challenge: The AMS Glossary of Meteorology defines *effective precipitation* both as the part of precipitation that reaches stream channels as direct runoff and, in irrigation, the portion of precipitation that *does not* run off and remains in the soil (AMS, 2022). To complicate the matter, there is also a definition for *precipitation effectiveness* which focuses on the portion of total precipitation used to satisfy vegetation needs (AMS, 2019b). While muddled definitions is an obvious overall problem, a secondary problem lies in the difficulty of applying this concept beyond vegetation. The concept of effective precipitation could be very beneficial in drought assessment if it considers ways to measure the water that is not getting to certain locations or industries that would usually expect it, including hydropower, fisheries, groundwater aquifers, or sector-specific water usages such as the outdoor recreation economy. Therefore, this concept needs a definition that can be applied within different contexts.

Despite the AMS definitions, for clarity and consistency within this section, the two terms are used in the following ways: *effective precipitation* describes the calculation proposed by Byun and Wilhite (1999); and *precipitation effectiveness* generally describes the concept of measuring the usefulness of precipitation within various systems.

Depletion Calculations Challenge: The choice of the effective precipitation reduction function remains unresolved due to the complexity of interacting parameters such as soil characteristics, topography, air temperature, humidity, and wind speed (Rončák et al., 2021). In order to accurately calculate effective precipitation for soils and working lands, runoff and evapotranspiration require precise calculations (Akhtari et al., 2008; Kalamaras et al., 2010; Kim & Byun, 2009; Kim et al., 2009; Morid et al., 2006; Roudier & Mahe, 2009).

Geographic Scope Challenge: Studies on calculating effective precipitation are not widespread and have been limited in their geographic scope and scale. Within the research community there is a clear need to identify a robust methodology to calculate effective precipitation at both the local and regional scale, especially considering the dynamic nature of precipitation variability on sub-monthly timescales, and the premise of a non-stationary climate. Adopting a drought metric that incorporates effective precipitation—or runoff-ratio or some other means of quantifying precipitation effectiveness—in its calculation would both allow for a more accurate assessment of water availability and assessments of drought in a non-stationary climate. A few geographic considerations and nuances are as follows:

- **In the Western United States,** establishing or revising a regional precipitation metric for mountainous and snow fed areas as a ratio of snow water equivalent (SWE)/precipitation (P), would account for the natural storage in snowpack. SWE vs. streamflow later in the year could provide insight into runoff and evaporation conditions. Tracking this over time would be an insightful measure of a changing climate. However, this will be challenging in Alaska, where thawing permafrost contributes to streamflow along with snowmelt.
- **In the Midwestern and Eastern United States,** a new or revised precipitation effectiveness metric could be soil moisture vs. precipitation to answer the question, "How much water made it into the ground as opposed to runoff?"

Priority Actions:

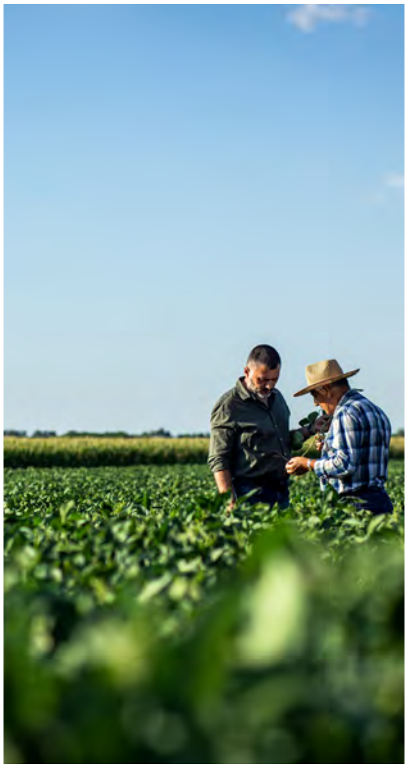
1. Consider a broader view of effective precipitation in drought assessment, beyond agriculture, as a way to quantify water scarcity for certain locations and industries.
2. Design a research-to-action framework to define and estimate precipitation effectiveness for different regions, times, sectors. Incorporate the evaluation of current infrastructure for precipitation effectiveness measurement/monitoring capacity.
3. Undertake a proof-of-concept study of precipitation effectiveness using a network of soil moisture sensors to quantify precipitation infiltration versus runoff.

4. Calculate effective precipitation at local and regional scales (e.g., gridded product) and incorporate effective precipitation—or some other means of quantifying precipitation effectiveness—into drought assessment.
5. Improve national soil moisture observations and data accessibility to inform drought assessment and disseminate related products to inform decision-making. This could include expansion of the efforts of the National Coordinated Soil Moisture Monitoring Network.
6. Develop a better understanding of how drought characteristics (e.g., duration, 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).

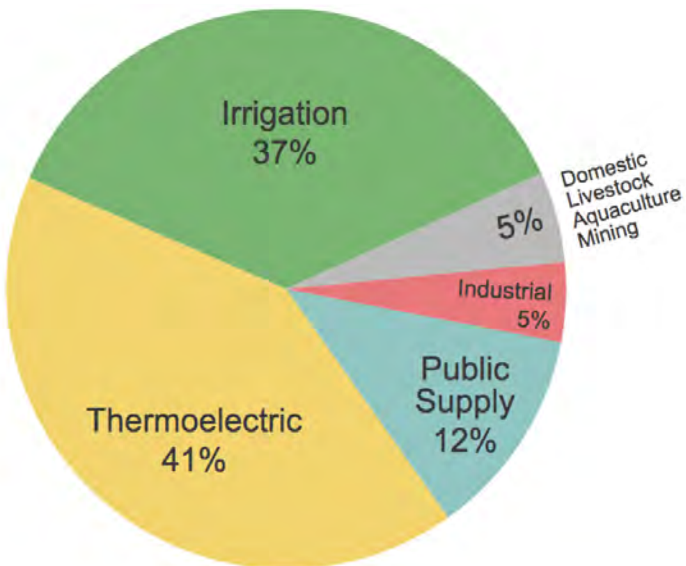
Research Questions:

1. How could the growing *in situ* soil moisture monitoring infrastructure be leveraged to improve soil moisture modeling?
2. What is the value of increased observations in heavily forested areas to remotely sensed products and models?
3. How can measurements and indicators of the hydrologic impacts of precipitation (or lack thereof) including soil moisture, shallow groundwater, and runoff, be increased and improved? How are management decisions accounted for?
4. Could soil moisture data be used to infer both available soil moisture and precipitation runoff information, and could this information be used in place of precipitation effectiveness?
5. How do changes to soil properties due to climate change, disturbance, and management practices impact infiltration, runoff, and soil moisture levels?
6. How can products addressing precipitation intensity normalize for spatial variability in soil infiltration capacity, based on soil type?
7. How can effective precipitation be quantified in real-time with current observation networks? How can changes in precipitation effectiveness over time be used to inform intensity-duration-frequency curves to support built infrastructure and account for precipitation changes at a location?
8. Once precipitation effectiveness is defined and quantified, how has precipitation effectiveness changed over time? How will it change in the future?
9. How does changing variability (especially intensity, but also other factors) impact precipitation effectiveness (e.g., precipitation returns to soil moisture, groundwater, reservoirs)? (See Scheff et al., 2022 for discussion on this topic as framed by the runoff-ratio).
10. Does groundwater infiltration fit into the concept of precipitation effectiveness (e.g., unconfined aquifers versus confined, pace of groundwater recharges)? How are aquifer recharge rates affected by changes in precipitation total and precipitation rates?

11. How does the gap between events (e.g., wetter but fewer events, longer dry spells) change characteristics and condition of soils to include more drying, and what are the ecological ramifications of these changes?
12. How can irrigation models inform our need to calculate precipitation effectiveness?
13. Can specific changes to precipitation duration and intensity translate to changes in effects, impacts, and usefulness of precipitation in a drought situation?
14. What time after the precipitation event should be examined (e.g., immediate, hours, integrated over some time period) to inform precipitation effectiveness?
15. Can thresholds be set for various sectors including water supply by comparing drought assessments with impacts as it pertains to precipitation events?



QUANTIFYING WATER DEMAND IN A CHANGING CLIMATE



How the United States uses water (2015). Source: USGS

Drought assessments are complicated by shifts, or potential shifts, in water demand from physical processes and human demands on water. This highlights the urgency for quantification of water demand across various sectors and cross-sector interactions (e.g., municipal water demands being met by transfers of agricultural water). In a warming climate, evapotranspiration is expected to increase, which leads to increased consumptive use of water. For instance, to satisfy crop needs under warmer conditions will require increased demand for both ground and surface water supplies. Quantifying these changes in evapotranspiration is complex and not accurately measured. Additionally, the seasonality of precipitation and intermittent dry periods—especially during the growing season—can create stress on plants as evaporation rates often outweigh observed precipitation. Crop choices, soil health and water management all contribute to changes in consumptive water use. For forest, shrubland, and grassland systems, water demand dynamics of the landscape and evapotranspiration rates are also impacted by precipitation patterns and increased heat, which can also increase wildfire risk. In addition, there are questions about the potential role of landscape and vegetation changes on water demand, such as rates of growth (Mankin et al., 2019; Ficklin et al., 2009) and transpiration and leaf-level stomatal closure (Grossiord et al., 2020; Yang et al., 2018; Eckhardt & Ulbrich, 2002).

Societal changes also impact water demand. For instance, new water-intensive industries, tourism, and population shifts have impacts on water availability (seasonal and sub-seasonal) and total demand. Understanding and monitoring changes in water supply availability and shifts in demand across sectors is fundamental to improving water management in a changing climate.

Priority Actions:

1. Accurately quantify water demand (anthropogenic and environmental) and how it is changing, including (1) monitoring of potential evapotranspiration and actual evapotranspiration, both nationally and locally, (2) developing evapotranspiration climatologies and trend analyses, (3) improving soil moisture monitoring, and (4) developing soil moisture climatologies.
2. Utilize water budgets across sectors to improve drought resilience for communities experiencing aridification and humidification in a changing climate.
3. Improve representation of atmospheric water demand in drought models and projections to more accurately account for potential evapotranspiration (PET) and actual evapotranspiration (AET) given the importance of land-atmosphere interactions for some drought events, and the impacts of land processes for sub-seasonal to seasonal forecasts and climate models.

Research Questions:

1. How can drought assessments incorporate quantified changes in water demand across sectors and natural demands (e.g., changes in evapotranspiration, land use, human behavior)? How can uncertainty that arises from human activities be quantified in drought assessment (e.g., people see conditions getting dry and then ramp up water use, thereby exacerbating drought)?
2. How are climate change-related phase changes in precipitation or terrestrial water sources impacting water availability (e.g., rain/snow, frozen/thawed permafrost, melting glaciers)?
3. What drives changes in water demand across different timescales for different sectors (e.g., agriculture, industry, tourism), and how can drought assessment and future planning consider times of highest demand?
4. How will evapotranspiration change with warming temperatures and changing climate, as this could place increased demand on water supply to satisfy crop needs and feed people? Should these changes be incorporated into drought assessment and response and how?
5. How can evapotranspiration and potential evapotranspiration (PET) be incorporated to improve assessment of current soil moisture conditions to understand how different plants (e.g., crops, rangelands, and forests) might experience stress?

EVALUATING DROUGHT IMPACTS AND HOW THEY ARE CHANGING

Dry periods develop into drought because the lack of precipitation has negative impacts on hydrology, ecosystems, and agriculture, which cascade through water dependent socio-economic systems (e.g., Wilhite & Glantz, 1985). The primary purpose of monitoring and assessing drought and its impacts is to reduce damage and identify and improve proactive drought resilience measures. This cannot be done without documenting how drought impacts social-ecological systems. Therefore, even without the considerations of non-stationarity, connecting drought indicators with drought impacts drives drought response. In a non-stationary climate, the characteristics of past droughts may not replicate or be good reference for future drought impacts, or the cumulative or composite outcome and cascading effects (e.g., drought and wildfire). Past drought response strategies and frameworks may be ill suited to address future droughts. Thus, non-stationarity creates increasing urgency to capture changing drought impacts across all types of droughts, sectors and communities. Understanding impacts includes the need to understand how human behavior can mitigate or exacerbate how impacts are felt as well.

At present, drought impacts on the agricultural sector are better quantified than for other economic sectors. Two areas where drought impacts are poorly documented are in socio-economic systems and ecosystems. Understanding and quantifying the full extent of drought impacts consistently is even more complex when considering cascading impacts (e.g., drought, wildfire, human health) and trying to tie an economic loss to a hazard like drought.

Improved understanding of drought impacts can come both from improved observations and documentation of impacts and from improved modeling of impacts within weather and climate models. Crop production and loss models and economic impact models can provide some indication of drought impacts. Accurate representation of the variation in vegetative responses within global climate models can also provide insights to how drought impacts might change in a non-stationary climate.

Priority Actions:

1. Investigate how well drought metrics relate to drought impacts for precipitation and temperature extremes and anomalies.
2. Further investigate the impacts of increased development (urban and rural) on water availability and drought indicators. For example, investigating the impacts of social-ecological systems (agriculture and community growth) on drought indicators.
3. Synthesize research on seasonality and changes around seasonality of drought and drought impacts on sectors beyond agriculture (e.g., tourism and recreation, public health). Identify and communicate which sectors (if any) might benefit from drought and which face additional challenges and any knowledge gaps that need to be addressed.
4. Collect systematic sectoral drought impacts for robust analysis, with use of emerging technologies such as artificial intelligence and upgrading existing condition monitoring systems.
5. Conduct research using compound event methods to examine amplified impacts of drought (e.g., drought and land subsidence due to groundwater depletion, river system declines and water quality issues, infrastructure failure due to low flows/low reservoir levels).
6. Investigate the cascading socio-economic impacts of drought and aridification across economic sectors and communities.
7. Evaluate and explore other indicators (e.g., snowpack, groundwater, soil moisture, evapotranspiration, wind, vegetation) as they relate to national and regional-scale drought impacts. This could include the integration of various indicators to look at the intersection of drought and wildfire (e.g., fuel load, fuel moisture) and wildlife species data to improve our understanding of ecological drought impacts and their timescales.
8. Continue to develop and strengthen regional partnerships to improve drought impact information exchange between scientists, practitioners, and stakeholders.

9. Improve representation of vegetation response and feedback (e.g., transpiration) in weather and climate models at a finer scale. This can be done using machine learning techniques and by improving model physics, parameterizations, spatial resolution, and computing resources to better represent vegetative processes.

Research Questions:

1. 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 impacts are not stationary either 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 rainfall impact).
2. How does the choice of reference period change the relationship between drought index and impact?
3. How does changing precipitation seasonality relate to seasonally-varying sectoral impacts? Can current decision calendars work with different sectors and communities to help define when precipitation is needed or expected and if and how the calendar is shifting?
4. What are the cascading impacts of drought across different sectors, and how are these changing over time? How could this information be incorporated into assessments to make them more actionable?
5. What insights are drawn from comparative analysis of impacts of historic, present-day, and future drought? How can those insights improve drought resilience and adaptation strategies?
6. Why do climate models predict dramatically different future trends in drought indicators (e.g., PDSI, SPEI) compared to drought impacts (e.g., soil moisture, runoff, vegetation) (Scheff et al., 2021 and 2022)?
7. How can land surface models be improved, with a focus on vegetation type, vegetation-land-atmospheric feedbacks, and soil layers, to better represent appropriate processes involved with non-stationarity?
8. How can models better represent vegetative processes to reflect vegetation contributions (e.g., transpiration, stomatal control, root depths, spatial and species heterogeneity, composition) to the hydrologic cycle during drought, including in future climate scenarios?
9. How can dynamic vegetation models be improved to include surface conditions (e.g., historical heavy livestock grazing pressures, post-fire effects, urban heat islands), which are valuable to capture post-disturbance behaviors, which change groundwater infiltration and precipitation recycling?

ASSESSING DROUGHT IN TERMS OF RISK

Effective drought risk management is based in conveying drought information and data in such a way that communities actively learn and adapt, while seeking to prevent and mitigate drought risk. Processes that build capacity across social, institutional, and scientific communities can lead to better assessment of drought risk and actions that lead to risk reduction. Determining a common understanding of drought risk as a product of drought as a hazard, exposure to the hazard, and levels of vulnerability (loss of assets/resources), can help with informed decision-making. Drought risk and mitigation is at the center of social-ecological systems, as drought hazard and human activities and decisions (e.g., land and water use/management) are intertwined, and those activities can exacerbate or alleviate risk.

Decision-makers in the U.S., who depend upon federal drought assessment tools (e.g., U.S. Drought Monitor, U.S. Drought Portal), are concerned about drought impacts on systems that differ in their ecological, economic, cultural, or other sensitivities. One way to provide actionable information about drought is to provide assessments that better capture the drought risk across these systems. Assessing drought risk is complex due to the variations in on-set (slow to fast), duration and extent of drought. Additionally, droughts can be compounded by the co-occurrence of other hazards (e.g., heatwaves, wildfires, flooding). These pose both direct and indirect impacts which can accumulate, affecting livelihoods and having deleterious impacts or consequences to individuals, communities, and systems. The biophysical and human context together determine the impacts of drought. Assessing drought risk is complex, and not all impacts are easily measured or quantified. Importantly, drought does not need to reach extreme levels, to have extreme risk, due to compounding impacts. Thus, drought risk requires an iterative approach that accounts for communities (e.g., infrastructure, water conveyance), economic livelihoods, and ecosystem services. These risk assessments need to be linked to vulnerability assessments to best understand those most at risk and levels of coping and capacity to respond and adapt. These risk and vulnerability assessments are needed for informed decision-making and the development and prioritization of actionable information. Drought risk is dynamic and is intended to acknowledge and account for non-stationarity in both the biophysical and human contexts. Improving drought risk assessments calls for identifying and quantifying the whole cost of drought, across social-ecological systems. Tools to address drought risk and promote adaptation can be utilized for those sectors at greatest risk. Tools like decision calendars can clarify timescales for decisions and periods where resources, crops, animals, or sectors might be at greater risk. Drought risk assessments and drought conditions need to be better linked to resource management decisions and decision calendars to inform how and when to provide more actionable information. Climate reference periods used for drought assessment can be adaptable and based on the experience of producers, water managers, forest managers, communities, etc. during drought.

Priority Actions:

1. Integrate the effects of land use and water management practices (historic, status-quo and adaptive) into drought risk assessments. For example, soil degradation and depletion of organic matter can lower water infiltration rates, soil storage capacity, and groundwater recharge rates potentially exacerbating the impacts of drought and enhancing drought risk.
2. Examine factors contributing to the adaptive capacity of a community, sector, or system to inform an appropriate selection of period of reference for drought assessment.
3. Conduct focus groups with urban and rural planners, resource managers and sociologists, agricultural and labor economists, and other interested social scientists to develop a more informed human dimension of drought effects.
4. Develop methods for addressing observation and information gaps, including capturing data from other knowledge systems, synthesis and summaries of information from disparate sources, and methods for integration of non-digital and analog data and information.
5. Conduct a review or study on how people perceive drought and aridity across sectors and regions. Specifically, identify modalities in reference periods and seek to determine how region, sector, and personal experience, memory, and knowledge influence perceptions of drought.
6. Fund impact-focused research to evaluate indicators in the context of adaptation practices and shifts due to climate change, given that these shifts can result in additional risk.

Research Questions:

1. What geographically and culturally-relevant techniques can identify, contextualize and classify dynamic drought risk?
2. What are the variations in personal perceptions of drought and aridity and how do these perceptions vary across regions, sectors and experience with drought? Do factors like safety nets, community support, communication methods, etc. play into drought perception? Can personal perceptions inform reference period selection for drought assessment?
3. What are the spatial, temporal and sectoral variations in drought risk assessments? What are the drought indicators and early warning signs of drought, used in these variations?
4. What facets of risk (hazard, exposure and vulnerability) are transforming with respect to a changing climate and environmental context (e.g., land degradation)? How does this transform decision-making with respect to population growth, agriculture, and land and water use changes?
5. Can socially-relevant, temporally and spatially analogous drought events be defined to help communities understand their drought risk? Can sector-specific and community-specific drought analogs be used to inform decision-making?

6. Would climate analogs—places and times globally that are climatologically similar to future conditions—assist in illustrating drought risk and potential mitigation strategies when planning for future change?
7. How can current understanding of climate non-stationarity be incorporated into assessments of extreme events of the past to better understand current and future risk? Can paleoclimate records provide a better understanding of past variability and drought to strengthen our understanding/detection of current non-stationarity?
8. What is the timeline for disseminating drought information to best support robust decisions and resource management actions on the ground? How does this vary by sector (e.g., municipal, agricultural, recreational, ecological)?




HIGHLIGHT: IMPACT-BASED MONITORING OF DROUGHT AND ITS CASCADING HAZARDS

Recent studies have highlighted the importance of integrating drought impact monitoring into drought-related hazard assessments (AghaKouchak et al., 2023). This shift to assessments focused on impacts more closely link drought to physical or societal impacts such as crop yield, food security, energy generation, while connecting drought to compounding or cascading hazards such as heatwaves, wildfires, floods and debris flows. Impact-based monitoring of drought can improve drought assessment to be more relevant to stakeholders and decision-makers involved in drought planning and response. Impact-based monitoring accounts for the impacts to different systems that are often not included in approaches used in the past, and more closely links assessment to the whole social-ecological system, from personal experiences to ecosystem impacts. Furthermore, accelerating and improving the integration of impacts into drought assessment is dependent on collection of consistent impact data across sectors and communities. This approach provides the opportunity to address some of the concerns about gaps in observation systems and *in-situ* monitoring data. Moving to impact-based monitoring would also open up the possibility of linking forecasts and outlooks to projected impacts, improving assessments of drought risk and communication, and education and support for adaptive strategies to improve drought mitigation and whole systems resilience.

There are various advancements highlighted in this report to implement impact-based monitoring. Progressing beyond a reactive approach to drought response to proactive drought risk management, can reduce harm and future risk, while creating resilience to the changing nature of drought as a hazard. Various adaptive measures offer opportunities for building future drought resilience which include linking early warning systems to impacts; understanding the role of resource management with water supply dynamics, availability and demand; standardizing data; and using artificial intelligence. These cross-cutting themes can be encompassed with improvements to impact-based drought monitoring, while other new data science approaches can extract and synthesize data on physical and societal drought impacts. Moving toward impact-based drought assessment to support informed decision-making will depend on addressing the research needs articulated in this report as well as current challenges with assessment approaches that are exacerbated by climate change.

ASSESSING POLICY THROUGH THE LENS OF NON-STATIONARITY

The technical workshop focused on the science and knowledge of drought assessment and improving our ability to assess the phenomenon of drought in a changing climate. However, workshop participants also identified considerations for related policy research, which are captured here to inform future discussions about the implications of non-stationarity to drought policies.

Priority Actions:

1. Evaluate drought assistance programs, over the life of the program, to determine what affected eligibility for programs, and if that could have led to inequities in the distribution of assistance.
2. Assess how communities and policy makers can leverage existing drought assessment products, programs, and policies to reduce drought risk.
3. Evaluate programs that use drought assessments to trigger disaster designation and programming to determine if they have or need to change due to current and future changes in climate.

Research Questions:

1. Have existing drought assessment products missed identification of flash drought conditions? If so, what are the economic consequences of missing conditions like flash drought in current assessment methods, and what information would be needed to inform policies that account for these consequences?
2. What are the barriers and opportunities within current policies to address aridification and the corresponding adaptation needs of aridifying communities? What drought and aridification information needs would help support the enhancement of responsive policies as it relates to drought assistance?

STRENGTHENING PLANNING, MANAGEMENT, AND ADAPTATION

Effective drought planning includes an integrated approach across management systems. This is necessary to create a comprehensive understanding of drought risk and vulnerability, which is unique to place and place-based systems and resources. This kind of systemic approach to drought planning and resilience building, provides the necessary knowledge exchange to address the inherent complexity, ambiguity and diversity of drought risk. This includes integration of monitoring data, network evaluation, and identification of priority areas based on compounding risk in certain sectors or areas that may not be otherwise identified. Increasing the diversity of actors and perceptions of conditions provides a broader portfolio for risk assessment and resilience strategies. Climate adaptive drought planning accounts for the capacities of the systems at risk and capabilities for adaptation. Additionally, climate adaptive drought planning allows for a holistic drought risk profile to drive the prioritization of drought resilience initiatives across social-ecological systems and technological assets. Ultimately, decision-makers need access to appropriate information, to identify priority areas, roles and responsibilities and informed decision-making that is proactive, and based on the best available knowledge and information. This becomes more relevant, and urgent, given the complexity that non-stationarity brings to this challenge. This approach relies on innovation, reliable data, decision-making tools, iterative learning (across scales), inclusive planning, policy support and funding for implementation. A whole system approach to building capacity and resilience depends upon trusted relationships (e.g., between service providers and end users), acknowledgement and integration of multiple knowledge systems, and information sharing across underserved communities and geographies.

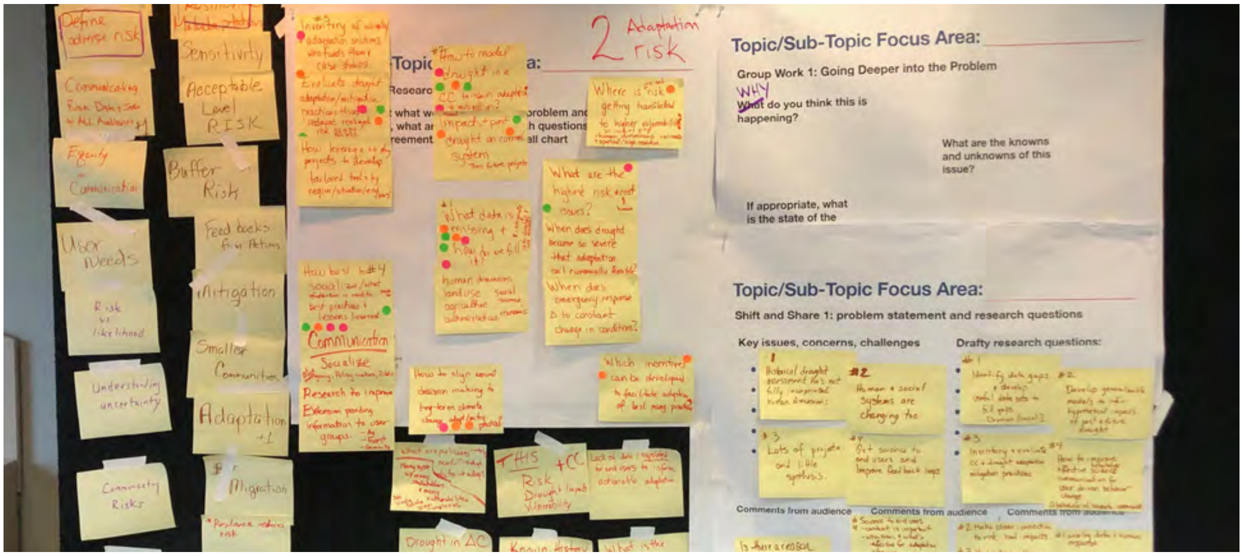
Priority Actions:

1. Ensure drought assessments support adaptive approaches to include the evaluation of actions, tools and programs to include transferability, quantified benefits, ease of application, etc.
2. Improve impact-based assessments of drought risk to inform the development of improved thresholds and triggers to support climate adapted drought planning.
3. Compile strategies for adaptation that address decision-making under uncertainty, using innovative solutions, and include information on return-on-investment and cost benefit analysis.
4. Identify sector and place-based community-specific drought indicators for drought assessment and to use as decision-making triggers and thresholds for adaptation strategies, projects and actions.
5. Assess economies of scale for drought resilience and strategies for cost effective drought resilience planning and adaptation strategies.

6. Develop a better understanding of how drought characteristics (e.g., duration, rate of intensification, spatial extent) might change in the future, and how these changes will impact response and policy decisions.

Research Questions:

1. What are the social-ecological system dynamics that influence drought management and response, which can either exacerbate or improve drought resilience? What effect does a non-stationary climate have on these dynamics?
2. What are the effects of adaptive or maladaptive measures on future drought hazards, exposure and vulnerability? What science is needed (or existing science that could be integrated) to support improved drought risk and vulnerability assessments and identification of adaptation strategies?
3. What perceptions (across sectors) to drought and aridification pose barriers and opportunities for improved drought assessment tools for climate adaptive drought planning and response?
4. 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?
5. What data, information, technologies and innovations will improve accurate drought scenario analysis to best inform climate adaptation planning across sectors? What misalignments exist between timelines of climate response triggers and management actions?



Notes from breakout session during the Drought Assessment and Climate Change Technical Workshop. Photo by Sylvia Reeves

IMPROVING COMMUNICATION AND COLLABORATIVE KNOWLEDGE EXCHANGE

Climate non-stationarity demands an increased focus on knowledge exchange. Including civil society and communities in grass-roots communication improves support for systems change and can enable transformative pathways towards resilience. This level of inclusivity can also guide decision-makers toward choices or trade-offs that were not otherwise transparent. This type of inclusive communication can build transformative partnerships and improve overall adaptive response, which ensures social accountability and increased transparency of public information. This can be realized through horizontal partnerships for shaping and sharing visions, increasing participation and mainstreaming resilience-based approaches. These horizontal partnerships support collaboration across governments, sectors and civil organizations to support citizen understanding and engagement. Other common approaches for mid-level or professional audiences include providing case studies, guidance on best practices, and peer-to-peer learning, which improve drought assessment, response, adaptation, and resilience policies (Elias et al., 2023; Longman et al., 2022). Climate change and aridification add to the complexity of communication challenges. For example, educating a community about why water conservation is no longer a sufficient drought mitigation strategy for a long-term drought or aridifying conditions. This level of communication requires transparency and trust building to achieve the community engagement necessary to reach the adaptive measures required for future water security. In addition, confidence and/or uncertainty in drought assessments can be communicated in a way that informs decision-making. Good communication resources are geographically and culturally relevant, including consideration for diverse languages spoken across audiences. In addition, as research outcomes lead to changes in drought assessments, the tools for communicating those changes will also change.

Priority Actions:

1. Leverage diverse and scalable communication vehicles to help explain how and why products are changing, when making improvements to strengthen existing drought assessment products to account for non-stationarity. Communicate non-stationarity in terms that work for knowledge exchange and outreach with a very wide drought information user-base.
2. Create a fact sheet, website, etc. for producers and land managers on the current state of knowledge regarding how precipitation intensity and other climate change signals affect the assessment of drought conditions using stories and case studies.
3. Create and conduct a sector-specific and/or community specific science communication training for climate services providers to assist them with better communication on what current drought assessments mean in the face of a changing and aridifying climate and how assessments are changing.

4. Explain and incorporate the concept of dynamic and cascading drought risk into existing resources and communication platforms.
5. Develop guidance for communicating drought assessment effectively, across civil society and service providers to promote transparency and avoid misinformation in an increasingly artificial intelligence dependent society.
6. Use metrics developed to characterize aridification—based on scientific consensus to quantify rates of aridification across the U.S.—to inform the framing of drought within the context of aridification in a changing climate.
7. Develop resources and best practices to communicate the concepts of drought and aridification to increase public awareness and ensure those resources are discoverable, accessible and trusted.
8. Provide resources to inform science education state standards (e.g., Next Generation Science Standards) and curriculum materials in K-12 to ensure the incorporation of accurate and relevant information on drought and aridification.
9. Given the drought to aridification continuum, consider what communication messages or tools could complement drought assessment products for risk-based decision-making.
10. Assess the value and effectiveness of aridification communication in order to adjust messaging and resources.

Research Questions:

1. What individual perceptions of drought influence how climate service providers communicate drought assessment in a changing climate?
2. Regarding communicating uncertainty, what is the most effective way to evaluate and communicate confidence and uncertainty in drought assessments, including how particular drought events are affecting particular sectors or regions? How can uncertainty and/or confidence in drought assessments be standardized while maintaining the usefulness of the information? Do users interpret these confidence intervals around drought assessment and translate them to impacts in a way that aligns with their experience of drought?
3. What improvements can be made in drought risk communication that provides equitable and inclusive language about drought in a changing climate?
4. As research results are available, what are the best methods for knowledge sharing at all levels, from grass-roots methods to disseminating case studies, lessons learned, best practices, etc. for improving drought assessment and management in a changing climate to accelerate their uptake?
5. What is needed to improve communication on the distinctions between aridification and drought? This includes understanding U.S. public perception of aridification vs drought and an exploration of how the framing of these two phenomena impacts decision-making.

CONCLUSION

NOAA's NIDIS and the USDA Climate Hubs leveraged a broad and experienced community of subject matter experts drawn from across sectors and levels of government to develop and integrate the information captured in this report. This report is the immediate outcome of the 2023 technical workshop, but ideally only a starting point for researchers and practitioners to advance drought assessment in the future. A subset of organizers and participants are currently working on a manuscript to further synthesize the information collected during the workshop to share the outcomes more broadly with the scientific and drought practitioner community. Improving drought assessment requires improving our scientific and technical understanding of drought, its drivers, and how they are changing. It also requires improving our understanding of the changing socio-economic, cultural, and ecological contexts of drought, as these influence vulnerability and resilience as much as drought itself. The continued improvement of drought assessment requires an inclusive approach to expand knowledge exchange, advance science, and support a resilient nation.

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APPENDIX 1: DEFINITIONS OF DROUGHT

Definitions taken from the AMS Glossary unless otherwise noted.

DROUGHT A period of abnormally dry weather sufficiently long enough to cause a serious hydrological imbalance.

Drought is a relative term, therefore any discussion in terms of precipitation deficit must refer to the particular precipitation-related activity under discussion. For example, there might be a shortage of precipitation during the growing season resulting in crop damage (agricultural drought), or during the winter runoff and percolation season affecting water supplies (hydrological drought). (AMS Glossary)

METEOROLOGICAL DROUGHT Meteorological drought is defined usually on the basis of the degree of dryness (in comparison to some "normal" or average amount) and the duration of the dry period. Definitions of meteorological drought must be considered as region specific, since the atmospheric conditions that result in deficiencies of precipitation are highly variable from region to region. (National Drought Mitigation Center)

AGRICULTURAL DROUGHT Conditions that result in adverse crop responses, usually because plants cannot meet potential transpiration as a result of high atmospheric demand and/or limited soil moisture. (AMS Glossary)

HYDROLOGICAL DROUGHT Prolonged period of below-normal precipitation causing deficiencies in water supply as measured by below-normal streamflow, lake, and reservoir levels; groundwater levels; and depleted soil moisture content. (AMS Glossary)

SOCIO-ECONOMIC DROUGHT Drought associating the supply and demand of some economic good with elements of meteorological, hydrological, and agricultural drought. (National Drought Mitigation Center)

ECOLOGICAL DROUGHT A prolonged and widespread deficit in naturally available water supplies—including changes in natural and managed hydrology—that create multiple stresses across ecosystems. (National Drought Mitigation Center)

FLASH DROUGHT An unusually rapid onset drought event characterized by a multiweek period of accelerated drought intensification that culminates in impacts to one or more sectors (agricultural, hydrological, etc.). (AMS Glossary)

SNOW DROUGHT A period of abnormally little snowpack for the time of year, reflecting either below-normal cold-season precipitation (dry snow drought) or a lack of snow accumulation despite near-normal precipitation, usually when warm temperatures prevent precipitation from falling as snow or result in unusually early snowmelt (warm snow drought). (AMS Glossary)

APPENDIX 2: LINKAGES TO NOAA AND USDA STRATEGIES

The priority actions and research questions contained in this report address and contribute to many strategic visions and plans across the Federal government. The list below is not exhaustive but gives a flavor of those linkages.

PLAN/STRATEGY	EXAMPLES OF LINKAGES
National Drought Resilience Partnership	Drought affects all facets of our society, from food production to water quality to public health, and there is a growing need to help communities, agriculture, businesses, and individuals threatened by drought to plan accordingly. With a focus on building long-term drought resilience, the National Drought Resilience Partnership (NDRP) is a federal partnership that is dedicated to helping communities better prepare for future droughts and reducing the impact of drought events on livelihoods and the economy.
FY2025 Office and Management and Budget and Office of Science Technology and Policy FY2025 Multi-Agency Research and Development Priorities	Address climate observations, monitoring, modeling, and research gaps ahead of the 6th National Climate Assessment, including in parts of our Nation beyond the contiguous United States; address risks and opportunities for future generations, including beyond 2100; and advance and use Indigenous Knowledge and social science research to achieve climate goals.
US Department of Commerce 2022–2026 Strategic Plan	**Strategic Goal 3:** Address the Climate Crisis Through Mitigation, Adaptation, and Resilience Efforts
NOAA Mission and Vision	**Vision 1.** To understand and predict changes in climate, weather, ocean and coasts; **Vision 2.** To share that knowledge and information with others
National Oceanic and Atmospheric Administration Strategic Research Guidance Memorandum FY2025	**Research Priority –** Climate Change: Review and develop metrics and research for their applicability in a changing climate. Historic algorithms might have reduced utility in a changing climate. For example, drought metrics in regions experiencing aridification lose meaning if the region shifts to permanent (in a historical context) drought condition. The emergence of climate surprises—events and phenomena absent in the historical record—bring forth challenges requiring new techniques for R&D.

PLAN/STRATEGY	EXAMPLES OF LINKAGES
NOAA FY22–26 Strategic Plan Building a Climate Ready Nation	**Strategic Goal.** Build a Climate Ready Nation
NOAA Science Advisory Board, 2021: A Report on Priorities for Weather Research	**Observations And Data Assimilation Priority Area 1.** Use and Assimilation of Existing Observations **Observations And Data Assimilation Priority Area 2.** Advanced Data Assimilation Methods, Capabilities and Workforce **Observations And Data Assimilation Priority Area 3.** Observation Gaps and Use and Assimilation of New Observations **Forecasting Priority Area 2.** Advancing Critical Forecasting Applications **Information Delivery Priority Area 1.** Highly Reliable, High-resolution Weather Information Dissemination **Information Delivery Priority Area 2.** Virtuous Cycle of Collecting and Analyzing Social, Behavioral and Interdisciplinary Observations **Foundational Elements Priority Area 1.** Science **Foundational Elements Priority Area 3.** Workforce Development
NOAA Science Advisory Board Report on Climate Information Needs for 5–10 Year Hazard Mitigation Planning Cycles	Drought Hazard 1. Develop nationally available products to track decadal changes in drought patterns **Recommendation 1:** Develop operational products to measure the timing (frequency), pace (how fast onset and development occurs), magnitude of deficits and impacts, and spatial resolution of drought events in a way that can track changes in metrics by decade in response to continued warming. Ensure that all capabilities are employed nationwide via the NIDIS program.
NOAA Research and Development Vision Areas: 2020–2026	**Vision Area 1.** Reducing societal impacts from hazardous weather and other environmental phenomena **Vision Area 3.** A robust and effective research, development, and transition enterprise
NOAA Oceanic & Atmospheric Research (OAR) 2020–2026 Strategy	**Goal 2.** Detect Changes in the Ocean and Atmosphere **Goal 4.** Drive Innovative Science
NOAA Climate Program Office 2015–2019 Strategic Plan	**Goal 1.** Partnerships **Goal 2.** Integrated Climate Research

PLAN/STRATEGY	EXAMPLES OF LINKAGES
NOAA Water Initiative Vision and Five-Year Plan & A Model of Service Delivery for the NOAA Water Initiative	**Goal:** To transform water information service delivery to better meet and support evolving societal needs.
NOAA National Weather Service Weather-Ready Nation Strategic Plan 2019–2022	**Goal 1.** Reduce the impacts of weather, water, and climate events by transforming the way people receive, understand, and act on information. **Goal 2.** Harness cutting-edge science, technology, and engineering to provide the best observations, forecasts, and warnings.
NOAA Physical Sciences Laboratory Strategic Plan 2021–2025	**Research Theme 1.** Physical Science for Water Resource Management **Research Theme 2.** Physical Science for Predicting Extremes
USDA Action Plan for Climate Adaptation and Resilience	**Action 1.** Build resilience to climate change across landscapes with investments in soil and forest health; **Action 4.** Increase support for research and development of climate-smart practices and technologies to inform USDA and help producers and land managers adapt to a changing climate. **Action 5.** Leverage the USDA Climate Hubs as a framework to support USDA Mission Areas in delivering climate adaptation science, technology and tools.
USDA Science and Research Strategy 2023–2026: Cultivating Scientific Innovation	**Priority 1.** Accelerating Innovative Technologies & Practices **Priority 2.** Driving Climate-Smart Solutions **Priority 4.** Cultivating Resilient Ecosystems
USDA Farm Service Agency Climate Change Adaptation Plan: July 2022	**Action Area 2.** Improve science, research, and data for understanding, measuring, and tracking climate related impacts and outcomes **Action Area 3.** Integrate climate vulnerability assessment and adaptation planning into customer-facing services **Action Area 5.** Leverage partnerships, networks, and collaboration to address existing climate change adaptation needs and innovate when considering future actions

PLAN/STRATEGY	EXAMPLES OF LINKAGES
USDA Risk Management Agency Climate Action Plan 2022	**Action B.** Implement incentives to encourage smart water use **Action C.** Implement incentives to encourage other climate-smart practices **Action D.** Continue updating program premium rates to reflect changes in risk due to climate change **Action E.** Continue updating program yields to reflect changes in output due to climate change
USDA Natural Resources Conservation Service Climate Change Adaptation Plan: July 2022	**Action Area 2.** Enhance science, research, and data for understanding, organizing, measuring, and tracking climate related impacts and outcomes **Action Area 3.** Integrate climate information into current business procedures, assessments, and opportunities **Action Area 4.** Ensure current and future applied conservation investments are reflective of climate change needs. **Action Area 6.** Strengthen partnerships and collaboration to address climate change

APPENDIX 3: LITERATURE REVIEW (EXCERPT)

The following are excerpts from a literature review that has been submitted for consideration at the Journal of Applied and Service Climatology.

Title: "Drought Assessment in a Changing Climate: A Review of Climate Normals for Drought Indices"

Authors: Joel Lisonbee, John Nielson-Gammon, Blair Trewin, Gretel Follingstad, Britt Parker

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Brief Timeline of Climate Normals

When assessing if a weather pattern can be considered abnormal it needs to be compared to a reference. The first use of the term "normal" to describe a comparable climate reference period in the meteorological literature was in a 1840 meteorological monograph by Heinrich Wilhelm Dove (1803–1879) (Guttman, 1989). Dove's use of the term "normal" had several different contexts, but the context that survived into the late 19th century is that "normal" was equivalent to the average or mean of a long series of observations (Guttman, 1989). "Originally this designation had been used for zonal means of climate elements, but the [WMO] adopted it for temporal rather than zonal means" (Landsberg, 1975, p.2).

The idea gained continued momentum in an essay titled *Suggestions on a Uniform System of Meteorological Observations* by Professor C. H. D. Buys Ballot (1817-1890), then the director of The Royal Netherlands Meteorological Institute. What Buys Ballot initiated in this essay would eventually become the standard in synoptical meteorology and ultimately lead to the formation of an International Meteorological Organisation (IMO) which was eventually succeeded by the WMO (Guttman, 1989; WMO, 2022). In a paper titled *Statistical Descriptors of Climate* by Guttman (1989), we learn some background as to why 30-years was chosen and some of the issues that arose right away from this decision.

In 1872, the International Meteorological Committee "resolved to compile mean values over a uniform period in order to assure comparability between data collected at various stations…The doctrine gradually developed that climate is essentially constant during intervals that are long compared to human experience. It was assumed that long-term averages would converge to this stable value or normal. International agreements eventually led to the compromise that the appropriate interval for computing a normal would be 30 years." (Guttman 1989, p.602; see also references therein and Landsberg, 1975)

In 1935 the IMO instructed member nations to adopt a standard 30-year reference period which included the years 1901 to 1930, inclusive. In 1956 the WMO updated the reference period and established the idea of regular updates every 10 years with the 30-year reference period ending in the most recent year ending with zero (WMO, 2007).

Historically, climatological normals have been used for two purposes. First, for comparison; "they form a benchmark or reference against which conditions (especially current or recent conditions) can be assessed" (WMO, 2007, p.6). Second, they are used for prediction; "they are widely used for predictive purposes, as an indicator of the conditions likely to be experienced in a given location" (WMO, 2007, p.6). While these applications of normals work well for most comparisons, they assume a stationary climate over time—essentially that the climate of today is sufficiently comparable to the climate of the past and the climate of the future. Early applications of climate normals warned about this assumption. Landsberg (1975) proposed that use of the concept of a climatological normal "did considerable harm" to the science of climatology. "One of the worst misinterpretations of the 'normal' concept was that a 'normal' value had, by itself, prognostic value for future events," (Landsberg, 1975, p.3). Guttman (1989) states, "the normals as they have been previously defined and published meet the needs of those making these kinds of comparisons. It is emphasized, however, that these comparisons imply very little about climatic change, non-random fluctuations, or extremes. They are simply an assessment of deviations from a reference" (Guttman, 1989, p.603).

Notwithstanding the WMO guidance for the use of a 30-year normal period, it has been shown that various climate normals ($N \neq 30$) can produce more accurate comparisons for various applications (Arguez and Vose 2011). While the focus of this review is on climate normals used specifically for drought assessment, a few non-drought applications of various climate normals include: a 50-year normal is ideal for the Atlantic Hurricane Season (Schreck et al. 2021); using an *optimal climate normals* technique showed the optimal normal for temperature is 10 years and for precipitation is 15 years (Huang et al. 1996; Livezey et al. 2007).

Drought Indices

This section reviews the introduction of climate indices specifically for drought assessment (hereafter "drought indices"; see Heim 2002; Quiring 2009; Mishra and Singh 2010; Dai 2011; Singh et al. 2022), and the period used to calculate the drought index. In this context the term "assessment" is used broadly to include drought monitoring and diagnosing—i.e., assessing when one is in a drought, and examining how extreme the individual droughts are in a historical context. It is not within the scope of this literature review to enumerate all the drought indices that have been produced (there are hundreds), but to look at commonly used indices and the amount of data used (reference periods, length of records, etc.) to assess drought.

Before enumerating some of these indices, it is worth pointing out that the selection of indices carries its own uncertainty in the overall drought assessment (Hoffmann et al, 2020; Satoh, 2021). Whether an index is selected for meteorological, agricultural, hydrological, socioeconomic, or ecological drought, can change the sign and magnitude of the drought assessment. This is why most studies focus on a single hydroclimate aspect. Satoh et al. (2021) and the IPCC (2012) articulate this as the issue of drought definition; "differences among drought definitions, particularly concerning drought categories, have the potential to be the dominant source of variance across northern high-latitude regions…The drought definition was the dominant source of uncertainty for over 17% of the global land area" (Satoh et al., 2021, p.10). In fact, McColl et al. (2022) recommend moving away from drought indices altogether when interpreting climate models because (1) they are redundant, (2) many work on the assumption that they are consistent in space and time, i.e., a stationary climate, and (3) they introduce definitional ambiguity.

Some Key Drought Indices Developed Before 1990

Within this literature search, the earliest discovered reference to a drought index is in a book by Foley (1957), which uses a cumulative precipitation anomaly based on all available data to quantitatively assess drought in Australia.

Palmer (1965) introduced what is now known as the Palmer Drought Severity Index (PDSI). The index is based on a water balance or hydrologic accounting approach to climatic analysis which allows for a calculation of the distribution of moisture excesses and deficiencies. This moisture supply-and-demand is estimated using a simple water balance model that uses temperature and precipitation as inputs and approximates the impact of potential evapotranspiration on soil moisture. This is generally accepted as the first attempt to objectively and numerically define drought. Palmer used the full record of data available; specifically for western Kansas, USA, this was from January 1887–December 1957 (71 years); and for central Iowa, USA, January 1931–December 1957 (27 years). In addition to the PDSI in 1965, the same paper by Palmer also introduced the Palmer Hydrological Drought Index and the Palmer Moisture Anomaly Index (commonly known as the Z-Index).

Another, less well-known drought index proposed in 1965 was the Rainfall Anomaly Index (van Rooy, 1965) which measured the rainfall anomaly, as calculated using the full period of record, against a 9-member classification scheme ranging from extremely wet to extremely dry.

Gibbs and Maher (1967) introduced the use of rainfall deciles as drought indicators. Rainfall deciles are calculated using all available data. As of the writing of this review, rainfall deciles are still used operationally in Australia as a way to assess drought (Australian Bureau of Meteorology, 2023).

In 1968, Palmer gave us another drought index based on the PDSI, this one specific to crops (Palmer, 1968). The Crop Moisture Index is the sum of an evapotranspiration deficit (with respect to normal conditions) and soil water recharge. These terms are computed on a weekly basis using PDSI parameters, which consider the mean temperature, total precipitation, and soil moisture conditions from the previous week. This index also uses the full period of record to calculate a climate normal.

Another commonly used drought index proposed in 1968 is the Keetch-Byram Drought Index (Keetch and Byram, 1968). Keetch–Byram drought index is a soil moisture deficit indicator usually used in fire risk assessment. It requires mean annual rainfall for the index calculation. When this index was first introduced, Keetch and Byram (1968) used all available data at that time.

The commonly used Aridity Index was introduced in 1977 (UNESCO, 1977), more to assess which climates are considered arid and less for diagnosing the occasional lows in precipitation variability. The Aridity Index is calculated simply as the precipitation divided by the potential evapotranspiration over a given time period (usually annually) at a given location or broader region. The original proposal for the Aridity Index averaged the annual precipitation and potential evapotranspiration over all available data for a location, but the index has been applied to shorter periods to establish changes in aridity over time (Greve et al., 2019).

Two new drought indices were introduced in 1980, but with specific hydrologic applications. These were the (Hydrologic) Total Water Deficit (Dracup et al., 1980) and the Drought Area Index (DAI, Bhalme and Mooley, 1980). The Total Water Deficit is calculated as the duration of drought multiplied by the average departure from "normal" within that duration. The DAI was developed as a method to improve understanding of monsoon rainfall in India, determining both flood and drought episodes using monthly precipitation (Bhalme and Mooley, 1980). Both used a full period of record, but could reasonably be calculated with a shorter reference period.

The Surface Water Supply Index, introduced by Shafer and Dezman (1982), is calculated by river basin based on snowpack, streamflow, precipitation, and reservoir storage using a Principal Component Analysis based on the full period of record at a location. This index classifies drought using normalized values in a scale similar to the PDSI. This is one example of how ingrained the use of the PDSI had become in the early 1980s.

The Soil Moisture Anomaly Index (Bergman et al., 1988) is another common drought index which requires "normal" precipitation and soil moisture values to assess drought. Bergman et al. (1988) did not define "normal".

Standardized Precipitation Index (SPI)

The SPI was first introduced by McKee et al. (1993), and it quickly became a very popular drought indicator that is widely used and studied. A few reasons for its popularity are that it is easy to calculate, relatively easy to understand and interpret, and input data (precipitation, either in situ, remote sensed or modeled) is easily available for most regions of the world. Special attention will be given to the SPI in this literature review for two reasons. First, in 2009 at the *Interregional Workshop on Indices and Early Warning Systems for Drought* held in Lincoln, Nebraska, USA, the SPI was recommended as the drought index to be used globally among national meteorological and hydrological services. This became known as "the Lincoln Declaration" (Hayes et al., 2011). Second, most of the studies that challenge the stationarity assumption in drought assessment use the SPI as a starting place for their argument.

A specific advantage the SPI has for multi-national drought assessments is that the only data it requires is total monthly precipitation, which is a variable routinely exchanged by WMO members through monthly CLIMAT messages (although coverage is still limited in many parts of the world, particularly Africa). Other drought indices often require additional variables and/or data for shorter time periods, for which historical and current data are often more difficult to obtain across international borders.

“The SPI is, conceptually, simply the precipitation anomaly divided by the Standard deviation where the mean and standard deviation are determined from past records” (McKee et al., 1993, Section 2.0).

In practice, however, there are additional steps that must be taken. Precipitation doesn’t fit a normal (or gaussian) distribution—partly because precipitation cannot have a negative value and partly because precipitation is skewed: below-average precipitation tends to be more common than above-average precipitation. This is most pronounced at shorter timescales and in arid or semi-arid climates. Precipitation distributions are most often estimated using a gamma distribution—although Guttman (1999) suggests a Pearson-III distribution is ideal.

Other Standardized Indices

Following the SPI there was a rise in standardized drought indices. These are usually indices that map the input data onto a normal distribution and divide the anomaly by the standard deviation to provide indices that can be compared with each other and over space and time (with caveats). Some of these include the Standardized Runoff Index from Shukla and Wood (2008) the Standardized Precipitation Evapotranspiration Index (SPEI) by Vicente-Serrano et al. (2010) and the Standardized Soil Moisture Index by AghaKouchak (2014). Ma et al. (2014) proposed a Standardized Palmer Index for hydro-meteorological use. Chanda and Maity (2015) introduced a Standardized Precipitation Anomaly Index. Gamelin et al. (2022) produced a standardized vapor pressure deficit drought index (SVDI). All of these indices categorize drought using the same or similar scale proposed by McKee et al. (1993). Namely, drought is considered mild when the index falls between 0 and -0.99, -1 to -1.49 is considered moderate drought, -1.5 to -1.99 is severe drought and anytime the index shows drought less than -2—or more than 2 standard deviations below the mean—this is considered an extreme drought (the SVDI is inverted such that positive values indicate drought conditions). The US Drought Monitor has used these values in conjunction with other drought indices to establish a drought severity index as follows: SPI values from -0.50 to -0.79 indicate abnormally dry (or a drought category of D0), -0.80 to -1.29 indicate moderate drought (D1), -1.3 to -1.59 indicate severe drought (D2), -1.60 to -1.99 indicate extreme drought (D3) and -2.00 or less indicates exceptional drought (D4).

All of these standardized indices assume a stationary climate and all but the SVDI (which used 1990–2012 reference period) use the full period of record to calculate the index. Many of these standardized indices have received similar criticism as the PDSI and the SPI, for example, Bartholomeus et al. (2014) noted that errors are introduced into the 6-month SPEI calculation based on the calibration period used.

Unlike the SPI, which considers only precipitation, many of these other indices attempted to incorporate a temperature component either implicitly or explicitly (e.g., evapotranspiration). One would expect indices which include temperature to show a stronger long-term trend in most climates, when compared to indices that use precipitation alone. A notable reference on this topic is the Intergovernmental Panel on Climate Change (IPCC) (2012). their Section 3.5.1 and inset Box 3-3, “The Definition of Drought”. This section points to what it calls “the issue of drought definition" and discusses the implications of using a drought index based on precipitation only compared to an index utilizing a temperature component (IPCC, 2012; Satoh et al., 2021). The IPCC's Fourth Assessment Report (IPCC, 2007) included drought assessments for a changing climate that mostly drew from multivariate drought indices (primarily the PDSI), which incorporated a temperature signal. The subsequent Fifth Assessment Report (IPCC, 2014) used a broader range of literature, which included the PDSI (and similar indices) but also included other indicators which use precipitation only. While using a broader range of drought indices would strengthen the assessment of drought in a stationary climate, the inclusion of precipitation-only drought indices for locations experiencing strong temperature and/or precipitation trends might weaken the accuracy of the drought assessment. Another example of this is Vicente-Serrano et al. (2010), which proposed the SPEI. They showed fairly good agreement between the SPI and the SPEI where a strong temperature trend was not evident but there were significant differences where temperatures increased over the analysis period (Vicente-Serrano et al., 2010, see their Figure 12, see also Vicente-Serrano et al., 2012). Stagge et al. (2015) applied a 30-year reference period to test various precipitation distribution differences between the SPEI and the SPI. And then, Stagge et al. (2017) used the divergence between SPI and SPEI to show that climate change is affecting drought analysis in Europe. These represent a few examples that specifically pointed to the inclusion of temperature (or temperature derived) variables within drought assessment and the divergence from precipitation-only based drought indices.

TABLE 2: Common drought indices and the originally recommended reference period for each.

INDEX NAME	REFERENCES	REFERENCE PERIOD ORIGINALLY USED OR RECOMMENDED	ENVIRONMENTAL VARIABLES
Cumulative Precipitation Anomaly	Foley (1957) Keyantash and Dracup (2002)	Anomalies are computed with respect to long-term (105 yr) means for each month. This likely was the full period of record at the selected location.	Precipitation
Palmer Drought Severity Index (PDSI)	Palmer (1965) See also Alley (1984) and Karl (1986)	Palmer used the full record for each site. Specifically, for western Kansas this was from January 1887—December 1957 (71 years) and for central Iowa, January 1931—December 1957 (27 years). Karl 1986 discovered that the PDSI is highly sensitive to the base period used and the Palmer Moisture Anomaly Index is less sensitive to reference periods.	Precipitation Temperature–Derived ET Local soil moisture
Palmer Moisture Anomaly Index (Z -index)	Palmer (1965)	Full period of record	Precipitation Temperature–Derived ET Local soil moisture
Palmer Hydrological Drought Index (PHDI)	Palmer (1965)	Full period of record	Precipitation Temperature–Derived ET Local soil moisture
Rainfall Anomaly Index	van Rooy (1965) see also Keyantash and Dracup (2002) and Kraus (1977)	Full period of record	Precipitation
Rainfall Deciles (RD)	Gibbs and Maher (1967) see also Keyantash and Dracup (2002).	Full period of record	Precipitation
Keetch–Byram Drought Index (KBDI)	Keetch and Byram (1968)	Requires mean annual rainfall for the index calculation. There is no clear indication of which period should be used to calculate the mean. The full record was used in the original derivation.	Precipitation and Maximum temperature

INDEX NAME	REFERENCES	REFERENCE PERIOD ORIGINALLY USED OR RECOMMENDED	ENVIRONMENTAL VARIABLES
Crop Moisture Index	Palmer (1968)	Full period of record	Precipitation Temperature
Aridity Index (AI)	UNESCO (1979) Zhao et al. (2019)	Full period of record	Precipitation Potential ET
Drought Area Index (DAI)	Bhalme and Mooley (1980) see also Keyantash and Dracup (2002)	Each individual season can be calculated as a stand-alone value and does not rely on previous seasons. The original derivation of this index used a 85-year record from 1891–1975 (representing the full period of record at the time) but this was only to calculate year to year comparisons rather than to derive the index.	Precipitation
Total water deficit (S)	Dracup et al. (1980)	Essentially uses the runs-sums method which calculates a truncation threshold (usually the long-term hydrologic mean as calculated using the full record at a location) and assumes stationarity.	Streamflow
Surface Water Supply Index (SWSI)	Shafer and Dezman (1982) Doesken et al. (1991)	Principal Component Analysis based on a full period of record.	Snowpack, Streamflow, Precipitation, Reservoir storage
Soil Moisture Anomaly Index	Bergman et al. (1988)	Requires "normal" precipitation and soil moisture values to compute this index. "Normal" is not defined by Bergman et al. (1988).	Soil Moisture
Standardized Precipitation Index (SPI)	McKee et al (1993) Edwards and McKee (1997) Hayes et al. (2011)	50-70 years, but assumes that more data is always better. This assumption has been supported by Guttman (1994, 1999), Wu (2005) This assumption has been challenged by Russo (2013), Hoylman (2022), Stagge (2015), Paulo et al. (2016), Rashid and Beecham (2019), Nunez et al. (2014), Park et al (2019), Shiau (2020), Song et al. (2020), Cammalleri et al. (2021) and others.	Precipitation

INDEX NAME	REFERENCES	REFERENCE PERIOD ORIGINALLY USED OR RECOMMENDED	ENVIRONMENTAL VARIABLES
Drought Severity Index (DSI)	Phillips and McGregor (1998)	Defined in terms of the 1961–90 mean—but assume the most contemporary 30-year reference period would be most appropriate.	Precipitation
Standardized Runoff Index (SRI)	Shukla and Wood (2008)	Full period of record	Runoff
The Standardized Precipitation Evapotranspiration Index (SPEI)	Vecente-Serrano et al. (2010)	The original derivation of the SPEI by Vecente-Serrano et al. (2010) used the full period of record (1910–2007) to derive the SPEI values. Subsequent studies have used shorter reference periods.	Precipitation Evapotranspiration
Standardized Soil Moisture Index	AghaKouchak (2014)	Full period of record	Soil Moisture

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APPENDIX 4: ASSESSING DROUGHT IN A CHANGING CLIMATE: STATE OF THE SCIENCE WEBINAR AGENDA

Drought Assessment in a Changing Climate Pre-Workshop Webinar
February 10, 2023 11:00 am–2:30 pm MT

Webinar Objective: To provide initial context and scientific background for understanding drought assessment challenges in the face of climate change, including the current state of the science and common terms (e.g., drought assessment, aridification vs. drought), and an understanding of what's at stake when drought assessment does not keep pace with a rapidly changing climate.

To review the recordings of all presentations, please visit:

https://www.drought.gov/events/drought-assessment-changing-climate-pre-workshop-webinar-2023-02-10

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TIME (MT)	PRESENTATION	SPEAKER
11:00 am	Welcome and Introduction and the Pathway to the Technical Workshop	Britt Parker, NOAA National Integrated Drought Information System/ CU-Boulder CIRES
11:10 am	Defining terms & contextualizing the problem: Why are we here?	Dennis Todey, USDA Midwest Climate Hub
11:20 am	How do we assess drought now through the US Drought Monitor?	Brian Fuchs, National Drought Mitigation Center
11:30 am	What does the USDM trigger?	Brad Rippey - USDA
11:35 am	Q&A	Facilitator: Holly Prendeville, USDA Northwest Climate Hub
11:45 am	What are the changes in climate and trends in variability, including extremes (e.g., drought) we have already observed across the nation?	Trent Ford, University of Illinois/State Climate Office
11:55 am	Why does non-stationarity matter for drought indices?	Zach Hoylman & Kyle Bocinsky, University of Montana/Montana Climate Office
12:05 pm	Q&A	Facilitator: Joel Lisonbee, NOAA NIDIS/CU-Boulder CIRES

TIME (MT)	PRESENTATION	SPEAKER
12:15 pm	What are the observed and projected changes in climate in the Northeast? And how does it make drought assessment challenging, even in a place that is getting wetter?	Art DeGaetano, Northeast Regional Climate Center
12:25 pm	What are the observed and projected changes in the climate in the Southwest? And how does it make drought assessment challenging, in a place that is increasingly more arid?	Andy Hoell, NOAA Physical Sciences Laboratory
12:35 pm	Q&A	Facilitator: Dennis Todey, USDA Midwest Climate Hub
12:45 pm	Break	15 min
1:00 pm	How does non-stationarity impact temperature, evapotranspiration, and other drought Indices and how that in turn impacts drought assessment?	Mike Hobbins, NOAA Physical Sciences Laboratory/CU-Boulder CIRES
1:10 pm	Approaches to Address Non-stationarity in Drought Indicators and Key Take-aways from the Literature Review	Joel Lisonbee, NOAA NIDIS/CU-Boulder CIRES
1:25 pm	Q&A	Facilitator: Elizabeth Ossowski, NOAA NIDIS/CU-Boulder CIRES
1:35 pm	Equity in Drought Assessment: Challenges and Solutions monitoring drought in a changing climate for tribal communities	Reno Red Cloud, Oglala Sioux Water Resources Department
1:45 pm	How are decision-makers employing current drought assessments? Where are the gaps in knowledge that your org/agency has identified? Why is a non-stationary climate consequential for decision making? Has your org/agency already changed drought assessment in the face of non-stationarity and if so how?	Seth Shanahan, Southern Nevada Water Authority
1:55 pm	—	Paula Cutillo, Bureau of Land Management
2:05 pm	—	Jim Prairie, Bureau of Reclamation
2:15 pm	Q&A	Facilitator: Julian Reyes, USDA Climate Hubs
2:25 pm	Wrap up and Pathway to the Workshop	Julian Reyes, USDA Climate Hubs

APPENDIX 5: ASSESSING DROUGHT IN A CHANGING CLIMATE TECHNICAL WORKSHOP AGENDA

Drought Assessment and Climate Change Technical Workshop
Agenda
February 28 – March 1, 2023
Boulder CO
Day 1: February 28, 2023

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TIME	SESSION	SPEAKER
8:00–9:00 am	**Breakfast/Networking**	—
9:00 am (15 min)	**Welcome and Set the Stage**	Britt Parker (NOAA NIDIS/CU-Boulder CIRES)
9:15 am (20 min)	**Opening Remarks**	Veva Deheza (NOAA NIDIS) Dr. Sarah Kapnick (NOAA chief scientist) Gloria Montaño Greene (USDA Deputy Under Secretary of Farm Production and Conservation)
9:35 am (15 min)	**Overview of Critical Topics and Process**	Joel Lisonbee (NOAA NIDIS/CU-Boulder CIRES) & Tamara Wall (Desert Research Institute)
9:50 am (15 min)	**Introductions in Your Topic Groups**	Break out into Topic Groups with facilitator
10:05 am (55 min)	**Identifying Sub-topics (in Topic Groups)**	Stay Topic Groups with facilitator
11:00 am (15 min)	**Break**	—
11:15 am (45 min)	**Sub-topic Group Work 1:** Further Define Sub-topic	Break out into Sub-topic groups with technical lead and process facilitator
12:00 pm (60 min)	**Lunch**	—
1:00 pm (100 min)	**Sub-topic Group Work 1 (continued as needed) and Group Work 2:** Identify Outstanding Research Questions	Sub-topic groups with technical lead and process facilitator
2:40 pm (20 min)	**Break**	—
3:00 pm (45 min)	**Sub-topic Shift and Share on Group Work 1 and 2**	Shift between sub-topic groups within your topic

TIME	SESSION	SPEAKER
3:45 pm (30 min)	**Sub-topic Groups Reconvene and Refine**	Sub-topic groups with technical lead and process facilitator
4:15 pm (15 min)	**Plenary: Wrap up and Review Day 2 Agenda**	Joel Lisonbee (NOAA NIDIS/CU-Boulder CIRES)
4:30 pm	**Optional Social Gathering—**Rayback Collective (2775 Valmont Rd. Boulder, CO)	—

Day 2: March 1, 2023

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TIME	SESSION	SPEAKER
8:00–8:30 am	**Coffee/Breakfast**	—
8:30 am (10 min)	**Welcome Back and Day 1 Recap**	Holly Prendeville (USDA Northwest Hub)
8:40 am (50 min)	**Sub-topic Groups Reconvene and Refine**	Sub-topic groups with technical lead and process facilitator
9:30 am (55 min)	**Sub-topic Group Work 3:** Identify short/long term recommendations/actions that can be taken now to improve drought assessment	Sub-topic groups with technical lead and process facilitator
10:25 am (20 min)	**Break**	—
10:45 am (45 min)	**Sub-topic Shift and Share on Group Work 3**	Shift between sub-topic groups within your topic
11:00 am (60 min)	**Sub-topic Group Work 3: Reconvene and Refine**	Sub-topic groups with technical lead and process facilitator
12:00 pm (60 min)	**Lunch**	—
1:00 pm (90 min)	**Topic Group Work:** Work within each topic to prepare to share across main topics	Topic Groups with facilitator
2:30 pm (15 min)	**Break**	—
2:45 pm (30 min)	**Topic Group Lightning Talks**	Plenary facilitated by Tamara Wall (Desert Research Institute)
3:15 pm (45 min)	**Facilitated Discussion on Next Steps**	Plenary facilitated by Tamara Wall (Desert Research Institute
4:00 pm (30 min)	**Thank You and Adjournment**	Julian Reyes (USDA Climate Hubs)