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).

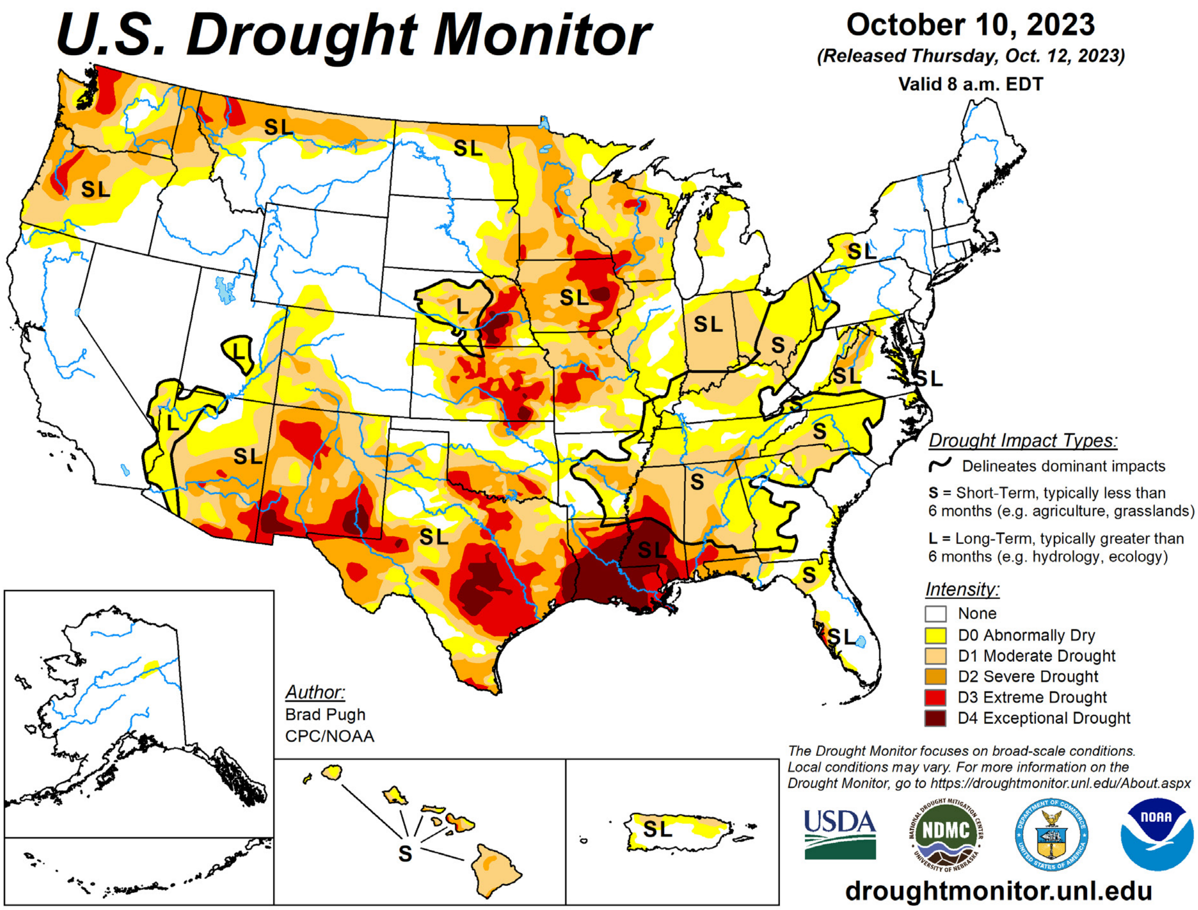
There are some downsides and precautions to using a shorter reference period. The severity of drought can change based on the reference period used (Karl, 1986; Paulo et al., 2016). For example, within the Western United States, the 30-year period from 1970-1999 was a relatively wet period, followed 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.