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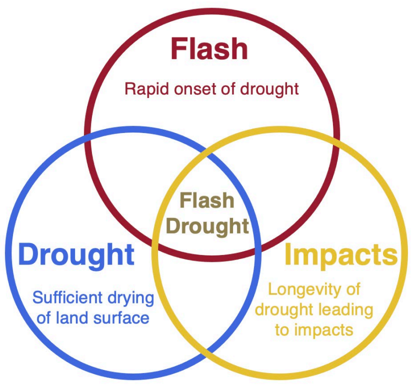
Conflict of Interest

The authors declare no conflict of interest.

Abstract

In the two decades since the advent of the term "flash drought," considerable research has been directed toward the topic. Within the scientific community, we have actively forged a new paradigm that has avoided a chaotic evolution of conventional drought but instead recognizes that flash droughts have distinct dynamics and, particularly, impacts. We have moved beyond the initial debate over the definition of flash drought to a centralized focus on the triad of rapid onset, drought development, and associated impacts. The refinement towards this general set of principles has led to significant progress in determining key variables for monitoring flash drought development, identifying notable case studies, and compiling fundamental physical characteristics of flash drought. However, critical focus areas still remain, including advancing our knowledge on the atmospheric and oceanic drivers of flash drought; developing flash drought-specific detection indices and monitoring systems tailored to practitioners; improving subseasonal-to-seasonal prediction of these events; constraining uncertainty in flash drought and impact projections; and using social science to further our understanding of impacts, particularly with regard to sectors that lie outside of our traditional hydroclimatological focus, such as wildfire management and food-security monitoring. Researchers and stakeholders working together on these critical topics will assure society is resilient to flash drought in a changing climate.

Graphical/Visual Abstract and Caption



Caption: We review the state of the relatively new science of flash droughts, which can develop faster than decision-makers can effectively respond, leading to amplified impacts: how much do we know about flash droughts and their impacts and how they are changing, and what are we missing?

1. INTRODUCTION

Against a backdrop of an unusually warm and dry spring across the contiguous United States (CONUS), a sudden intensification of drought began across the lower Ohio Valley (around Paducah, KY) in mid-April, 2012. In this region, the United States Drought Monitor (USDM; Svoboda *et al.*, 2002) reported that conditions were merely “abnormally dry” (USDM drought category D0) on May 8; however, they rapidly deteriorated to the most extreme drought category (D4, or exceptional drought) in only two months. This drought flashed across the agricultural heartland of the United States as its epicenter migrated west across the Great Plains over the next few months. By September 25, the USDM showed that drought had spread across 65% of CONUS, with over 20% of the area in drought at the extreme (D3) or exceptional (D4) levels. This was the fourth largest drought by areal extent since 1895 (Knapp *et al.*, 2015), and the celerity of its intensification took practitioners by surprise, stressing stakeholders across many sectors. By the end of the drought, United States agricultural losses exceeded $30 billion, with shocks to global food security transmitted through disruptions to the worldwide supply of grain and oilseed products (Boyer *et al.*, 2013).

While drought itself has been simply defined as “insufficient water to meet needs” (Redmond, 2002), it is challenging to classify different types of drought due to the diversity of compound and cascading causes and effects. Traditionally, drought has been classified as meteorological, hydrological, agricultural, ecological, or socioeconomic based on the duration of the abnormally dry weather, the location within the water cycle of drought impacts, and their complexity (Crausbay *et al.*, 2017; Wilhite & Glantz, 1985). Flash droughts are a subset of all drought types that are characterized by unusually rapid intensification, either to begin a drought or to exacerbate an existing drought (Otkin *et al.*, 2018a, 2022). The earliest mention of flash drought-like events is the “sukhovey,” which was first noted in the southern plains of Russia and later examined in the plains of North America (Lydolph, 1964; Lydolph & Williams, 1982). These events were characterized by hot and dry air masses with extended precipitation deficits that led to rapid plant stress and wilting. Two studies in the early 1980’s (Namias, 1982, 1983) were possibly the first to mention “rapid drought development” in the context of the 1980 U.S. Southern Plains Drought, noting that this event developed from a combination of little precipitation and excessive heat. The term “flash drought” was first used in the published literature in 2002 to describe rapidly intensifying drought conditions (Svoboda *et al.*, 2002; Peters *et al.*, 2002). Research on flash drought has considerably increased during the past decade in response to several high-impact events such as the 2012 flash drought across the central U.S. (Lisonbee *et al.*, 2021).

The fundamental development of flash drought can be illustrated as the intersection between three critical factors: rapid development (i.e., the “flash” component); sufficient moisture deficits and drying of the land surface (i.e., the “drought” component); and impacts associated with intensity of the moisture deficits and their longevity (Figure 1). A flash drought defined by this triad provides a distinct difference from other dry events, such as a short-term dry spell in which rapid onset is present but drought and impacts are not reached, or conventional, slowly developing droughts in which drought and impacts are experienced but rapid onset does not occur (Otkin *et al.*, 2022). Further, flash droughts often involve the compound impact of below-average precipitation and above-average atmospheric evaporative demand associated with higher temperatures, lower humidity, stronger winds, and increased solar radiation (via reduced cloud cover; e.g., Hobbins *et al.*, 2016). This combination of drivers represents a central baseline from which flash drought can be characterized.

While it is important to note that flash drought events impact regions worldwide, an example of the rapid development of flash drought is provided here using the 2017 flash drought over the Northern Great Plains of the United States to highlight the spatiotemporal evolution of the event in combination with the wide ranging impacts of flash drought (Figures 2 and 3; Hoell *et al.*, 2019a, 2019b, 2020; Pendergrass *et al.*, 2020). At the beginning of May 2017, soil moisture values were high across the region, but rapidly decreased to below the 20th percentile by the beginning of June (Figure 2). Very little precipitation fell during May, with soil moisture depletion accelerated by above-average temperatures and solar insolation in early May and early June (Figure 2). This period of rapid intensification satisfies the “flash” component of flash drought, with soil moisture values falling below the 20th percentile ensuring that drought had developed during the period of rapid intensification. By July 2017, the USDM weekly discussions began to report severe impacts across eastern Montana and western North Dakota following the rapid intensification period, with extreme and exceptional drought conditions reached by the beginning of August (Figure 3). Impacts included agricultural losses, increased wildfire occurrence, and damaged ecosystems (Hoell *et al.*, 2020). As such, the three factors–rapid drought intensification, drought conditions, and impacts–allow this event to be classified as a flash drought. The primary drivers associated with flash drought development–including precipitation, temperature, cloud cover, and wind speed–are also depicted in Figure 2. This case study highlights the compounding effects of below-average precipitation and enhanced evaporative demand that are important for the development of flash drought.

In this paper, we review the state of the science of flash droughts. Articles considered for inclusion in this review were searched for on the Web of Science with the phrase "flash drought" or "flash droughts". Papers were only included in this review if they contained either of the two phrases within the article and contained at least one analysis of flash drought. The requirement to contain analysis of flash drought removes articles that only briefly mention the term "flash drought" or "flash droughts" and would not be beneficial to a state of the science review of flash drought. After applying these criteria, 138 papers were found to be published on the topic as of August 2023 (Table 1). Following a literature review of the 138 articles, this paper includes a brief history of flash drought definitions, indicators, and climatological characteristics, along with the primary drivers of flash drought development, subseasonal-to-seasonal forecasting and climate change projections for flash drought, relevant social science research, and cascading impacts. We conclude the synthesis with thoughts on the future direction of flash drought research.

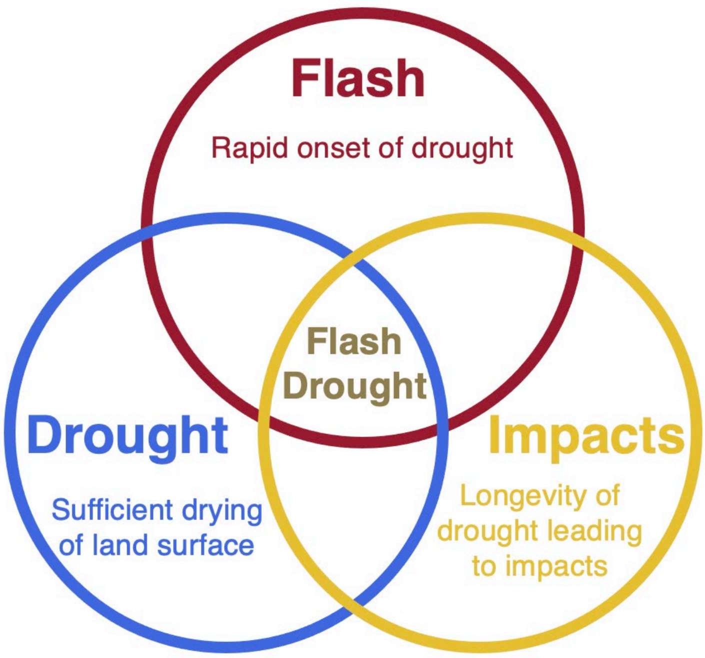


Figure 1. A Venn diagram illustrating the triad of components that form the basis of flash drought. The intersection of these three components (flash, drought, and impacts) defines a flash drought event.

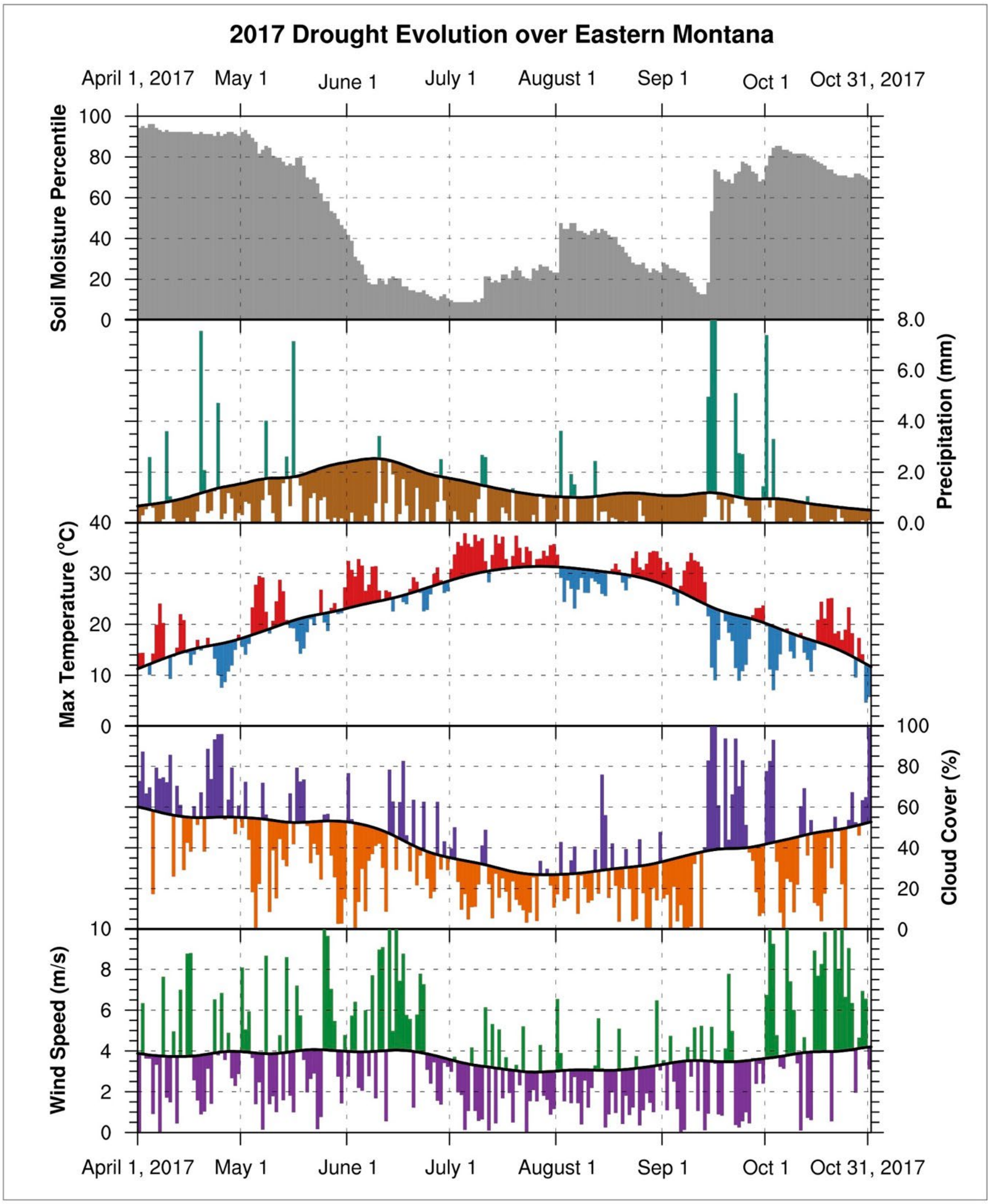


Figure 2. Times series of flash drought evolution in Eastern Montana in 2017. For Eastern Montana (defined as the region bounded by 46˚N-49˚N and 109˚W-104˚W), from top to bottom: daily soil moisture percentile (calculated relative to data for 1916-2017); departures from the climatological average (1950-2017; solid black line) of daily precipitation (mm); departures from the climatological average (1950-2017; solid black line) of daily maximum temperature (°C); departures from the climatological average (1979-2017; solid black line) of mean daily cloud cover (%); and departures from the climatological average (1979-2017; solid black line) of mean daily horizontal 10-meter wind speed (m/s) from April 1, 2017 to October 31, 2017 (from Hoell et al., 2019b).

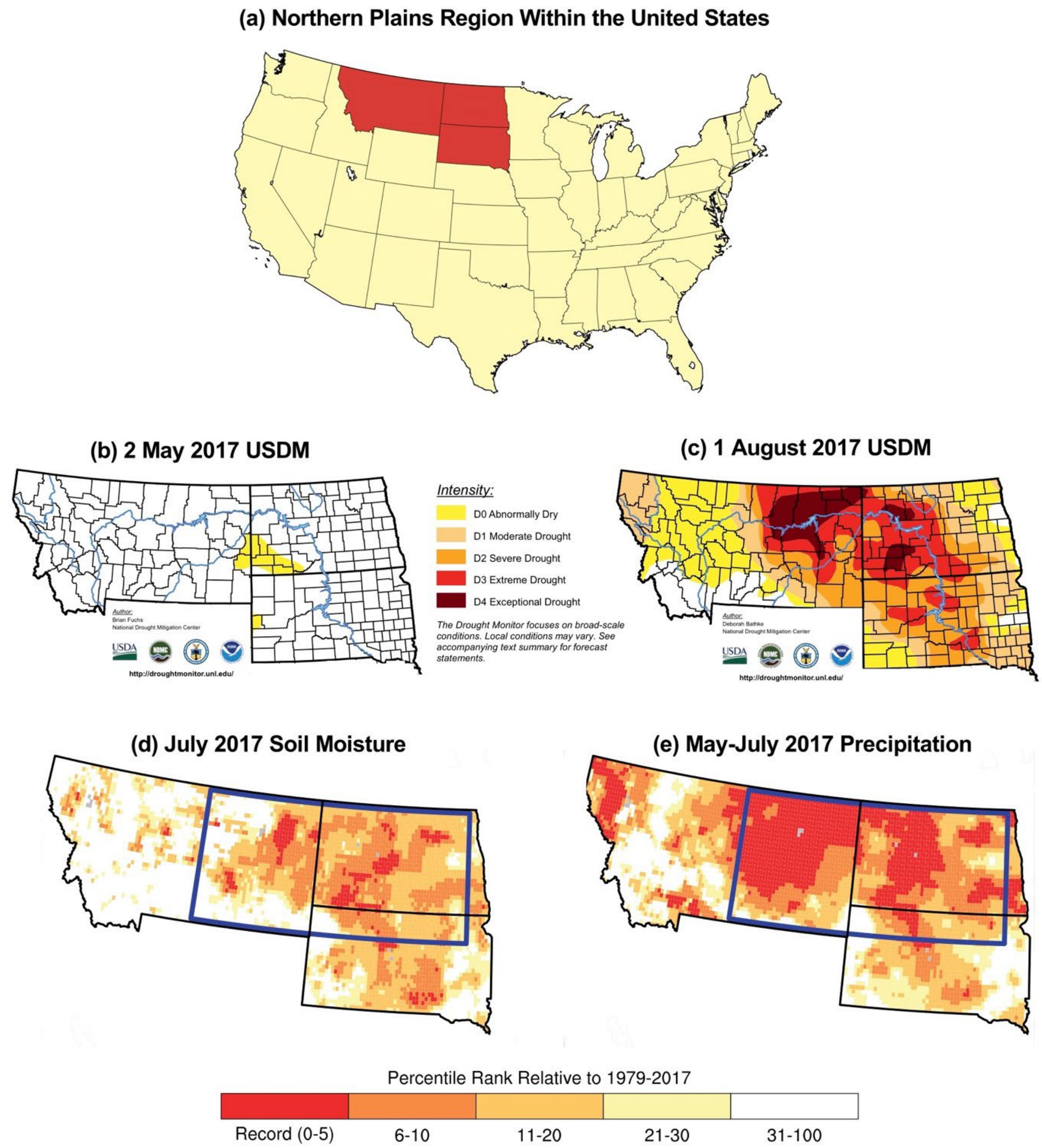


Figure 3. Spatial evolution of flash drought in the Northern Great Plains in 2017. (a) Location of the northern Plains as examined in the 2017 drought case study. (b-c) U.S. Drought Monitor on 2 May and 1 August 2017, respectively. Also shown are percentile ranks of (d) July 2017 1-meter soil moisture and (e) May-July 2017 precipitation based on the NLDAS-2 data (from Hoell et al., 2019a). The blue boxes indicate the Northern Great Plains region studied in Hoell et al. (2019a).

2. A FLASH DROUGHT DEFINITION FRAMEWORK

Since the advent of the term "flash drought" in Peters *et al.* (2002) and Svoboda *et al.* (2002), there have been both a strong desire to define the phenomenon and a lack of consensus on the proper definition. As Otkin *et al.* (2018a) and Lisonbee *et al.* (2021) note, most flash drought definitions to date emphasize either (1) the duration or (2) the swiftness of onset and intensification.

For example, Senay *et al.* (2008) define flash drought as a "short-term" yet "severe" drought event, with a focus on both the event duration and severity. This emphasis on duration and severity is adopted by Hunt *et al.* (2009) and Mo and Lettenmaier (2015, 2016). Many of these definitions either include an explicit maximum-duration criterion or are formulated such that relatively short duration events (e.g., 2-4 weeks) are defined as flash droughts. Concurrently, a lineage of studies emphasizes the rate of intensification for flash drought definition, largely beginning with Anderson *et al.* (2013) and Otkin *et al.* (2013). These definitions include an explicit or implicit celerity criteria for drought onset and/or intensification, such as a sufficiently large decline in soil moisture over a relatively short period of time (e.g., Ford & Labosier, 2017). See Lisonbee *et al.* (2021) for a more detailed discussion of the various flash drought definitions proposed.

Definitions of these terms (event duration and intensification) vary with perspective: in the case of conventional drought, for a stakeholder, the duration of a drought event may be defined as the period over which they feel impacts, whereas from a scientific perspective, it may be the period for which an anomaly of a meteorological variable like precipitation or a response variable like soil moisture exceeds a given threshold. From either point of view, a conventional drought extends from drought onset to the end of the amelioration period—whether marked by the end of impacts or a return to mean hydrometeorological conditions. For flash drought, however, these definitions are complicated because though rapid intensification is the key characteristic that distinguishes them from conventional droughts, flash droughts may also be the first phase of a long-term drought, or a period of rapid intensification within an existing drought.

The debate over flash drought definition may seem pedantic at first glance; however, the framework on which these definitions are based can characterize different weather phenomena, and therefore can lead to significantly different results when studying the historical occurrence, physical drivers, predictability, and the future prognosis of flash droughts (Liu *et al.*, 2020b; Otkin *et al.*, 2022). From this perspective, flash drought definitions should emphasize the rapidity of onset or intensification and ensure that the event is of sufficient severity and/or duration to cause tangible impacts (e.g., agricultural yield loss, reduced vegetation health, ecological degradation, and diminished water resources), thereby fulfilling both the flash and drought requirements, as shown in Figure 1 (Otkin *et al.*, 2018a). This framework ensures both the celerity and dryness components of flash drought are included in any definition, and also allows the flexibility of developing definitions to fit for specific parameters, sectors, and geographic regions (Otkin *et al.*, 2022). For example, this framework has been applied to soil moisture in Australia (Parker *et al.*, 2021), southeast Asia (Kang *et al.*, 2022) and India (Mishra *et al.*, 2021), evapotranspiration (ET) or evaporative demand in Russia (Christian *et al.*, 2020), evapotranspiration in Australia (Nguyen *et al.,* 2023), precipitation in Europe (Noguera *et al.*, 2021), and vegetation response in the US (Mohammadi *et al.*, 2022). That said, studies have shown large disparities in the climatological characteristics (e.g., frequency, intensity, etc.) and drivers of flash drought when different definitions based on the same dryness-celerity-impact framework are used (Osman *et al.*, 2021; Mukherjee & Mishra, 2022). These, and other works, suggest attribution, hot spot, and trend analyses may be very sensitive to the variable and specific thresholds used to define flash drought (e.g., Hobbins *et al.*, 2021). In lieu of a single definition that overcomes these issues and can accurately describe all aspects of flash drought, future flash drought research should clearly articulate the reasoning behind the use of a specific definition and include a sensitivity analysis to reduce the uncertainty caused by the diversity of flash drought definitions.

3. FLASH DROUGHT MONITORING & INDICATORS

Drought may be defined as a sustained and impactful departure from the climatological balance of water supply to, and water demand from, the land surface; flash drought adds to this a requirement of rapid intensification. Therefore, in the following sub-sections we examine the phenomenon of flash drought in the context of supply and demand. Irrespective of the definition, most studies have denoted two ingredients necessary for flash drought: (1) precipitation deficit and (2) high evapotranspiration (ET) and/or evaporative demand (Otkin *et al.*, 2013). The combination of reduced water supply and heightened water demand elicit rapid soil moisture and groundwater drawdown that can lead to vegetation moisture stress, reduced stream baseflow, and lower surface water and municipal or private well levels. Flash drought monitoring and indicator development have largely occurred through the lens of this general framework, with foci on precipitation (Noguera *et al.*, 2020; Fu & Wang, 2022), evaporation or evaporative demand (Otkin *et al.*, 2013; Hobbins *et al.*, 2016; McEvoy *et al.*, 2016a; Christian *et al.*, 2019a), soil moisture (Ford & Labosier, 2017; Osman *et al.*, 2021), and vegetation conditions (Otkin *et al.*, 2016; Ahmad *et al.*, 2022). Lisonbee *et al.,* (2021) separate flash drought indicators into similar categories and also include a temperature-based monitoring category, but we should note that the effects of temperature on flash drought are captured by the evaporation and evaporation demand-based indicators, and that relying on temperature-based drought indicators is not without risk (see below). From an operational monitoring perspective, the suite of potentially effective flash drought indicators can act as a complementary set of tools by which to inform flash drought response and management. However, the limitations and uncertainties with each tool must be well measured and communicated between research and operations to ensure proper use of any individual indicator (Otkin *et al.*, 2022). In this section we review the general characteristics, advantages, and disadvantages of each class of indicator. While we cite specific indicators within a class (e.g., precipitation-based indicators), we do not remark on the effectiveness or accuracy of any specific indicator relative to other indicators in that class. More research is needed to compare the dozens of flash drought indicators across a diversity of climates, conditions, and events before we can conclusively determine the optimal flash drought indicators for a given location.

3.1 Precipitation Indicators

As with any drought, precipitation deficits play an important role in determining the speed, intensity, and duration of a flash drought event (Koster *et al.*, 2019). However, in the case of flash drought, the widely held supposition is that below normal precipitation is a necessary but not sufficient condition (Otkin *et al.*, 2013). Meanwhile, other studies have found the role of precipitation in flash drought development is regionally variable, with a stronger contribution in monsoon climates (Han *et al.*, 2023; Mahto and Mishra, 2020). While the role of precipitation in flash drought is widely recognized, few precipitation-based flash drought indicators have been developed.

Most research and operational monitoring efforts use precipitation-based indicators that were developed for conventional droughts, such as the Standardized Precipitation Index (SPI; McKee *et al.*, 1993) and the Standardized Precipitation-Evapotranspiration Index (SPEI; Vicente-Serrano *et al.*, 2010). These tools are popular due to their effectiveness, relative ease of calculation and use, and the abundance of precipitation data and information in many areas of the globe. Both SPI and SPEI have been shown to have some utility for flash drought monitoring, with variability in performance between regions and events (Hoffman *et al.*, 2021). SPEI, in particular, has gained increasing use in recent years because it includes both precipitation and evaporative demand.

The warming global climate has also created a growing need for better consideration of temperature and evaporative demand on drought development (Stagge *et al.*, 2017) and increasing temperatures have been shown to affect flash drought characteristics in many regions (Noguera *et al.*, 2022; Yuan *et al.*, 2023). However, as with evaporation and evapotranspiration-based indicators, SPEI has the potential to mis-estimate drought intensity and duration if the demand part of the equation is unrealistic or not properly calibrated (Park *et al.*, 2018). In addition, the effectiveness of SPEI for flash drought identification depends on the accuracy of potential evapotranspiration (PET) estimation. For instance, PET estimation based on methods that are highly sensitive to temperature (Thornthwaite) can lead to overestimation of the frequency and intensity of flash droughts (Aadhar and Mishra, 2020). Penman-Monteith and energy budget-based methods for PET estimations can enhance the ability of SPEI in accurately capturing the onset and intensity of flash droughts (Aadhar and Mishra, 2020). Furthermore, these issues can be exacerbated when using temperature projections to estimate future drought risk (Aadhar and Mishra, 2020; Zhang *et al.*, 2022a).

3.2 Evaporation & Evaporative Demand Indicators

Evaporative demand (E_0) represents the demand side of drought; it is the energetic maximum of ET, or the “thirst of the atmosphere.” Evapotranspiration (ET) is the flux of surface moisture to the atmosphere in response to that demand, and is mediated below E_0 by the availability of moisture to evaporate. Both fluxes relate physically to the supply side of drought (precipitation) and to each other, though these relationships vary across the hydroclimatic spectrum. At the initiation of drought, if the surface is moist enough, atmospheric evaporative demand increases in response to increased sensible heating (e.g., from increased surface heating due to decreased cloudiness). This increases ET in response—a parallel relationship—at least until there remains insufficient soil moisture to meet the increased demand. At this point, ET and latent heating decline, releasing further sensible heating, causing E_0 to increase further—in the complementary relationship first described by Bouchet (1963).

The power of E_0 acting in this parallel-complementary relationship sequence is described in Hobbins *et al.* (2016): E_0 may be considered a driver of increasing ET in wetter conditions, and a rapid response to falling ET in drier conditions [see also Bouchet (1963) and Hobbins *et al.* (2004)]. However, all else equal, unlike ET, E_0 always increases under the drying conditions of drought onset. Because the response of E_0 to drying is generally observed sooner than that of ET due to physical dynamics, and because the observational data are more tractable in both requirements and availability, E_0 is useful in both early warning of drought onset and flash drought monitoring. That E_0 is a robust, leading indicator of drought motivated the development of the Evaporative Demand Drought

Index (EDDI; Hobbins *et al.*, 2016; McEvoy *et al.*, 2016a)—a multi-scalar, low-latency drought index that uses only E_0 as an input. EDDI has been shown to permit early warning of drought and of flash drought development (Hobbins *et al.*, 2017). An attempt to codify this sensitivity in a flash drought detector based on 2-week EDDI (Pendergrass *et al.*, 2020), however, resulted in far too many flash droughts detected in areas of CONUS with highly variable E_0, such as the northeastern United States and Pacific Northwest (Hobbins *et al.*, 2021). It may be that E_0 is simply too sensitive a driver of the moisture imbalance that drives drought, resulting in too many flash droughts in such areas and therefore a high level of false alarms. It is worth emphasizing that E_0 is not an impact of drought, but a driver (when the surface is wet) or a response (when the surface is dry), whereas ET is a direct measure of plant's productivity and may itself be considered an impact.

It is crucial to note that while various E_0 parameterizations have arisen to meet a variety of needs—climatology, reservoir management, irrigation planning and management, crop-stress and drought monitoring—they are not all created equal (e.g., Dewes *et al.* 2017). The scientific theory underpinning most physical E_0 parameterizations has preceded by decades the availability of data required to operationalize that science: for example, the meteorological and radiative observations required to exploit the Penman (1948) fully physical parameterization of large-scale evaporative demand did not become widely available for many decades, and this led to the popularity of empirical, temperature-based procedures such as that of Hargreaves and Samani (1985). Parameterizations that are not fully physical (for example, that ignore humidity, solar radiation, and wind speed in favor of a reliance on temperature alone) have long sat hidden at the heart of our most popular drought metrics; a seminal example is that of the Palmer Drought Severity Index (PDSI; Palmer, 1965), which uses a temperature-based approach to E_0 that yields drought trends of the wrong sign at secular timescales (Hobbins *et al.*, 2008). Even the first iteration of the more-recent and popular SPEI (Vicente-Serrano *et al.*, 2010) used a temperature-based Thornthwaite (1948) approach, though this has since widely been replaced by the fully physical Penman-Monteith reference ET (Monteith, 1965). While it is important for users of flash drought indices to recognize these nuances and dangers of potential misinterpretation, their impact on the utility of temperature-based approaches is open to debate as the temperature signal in flash drought is, in fact, very rapid.

As E_0 represents a theoretical limit to ET (such that the flux of ET cannot exceed the flux of E_0 over the same time period), the ratio ET/E_0 (known as "evaporative stress" or "reference ET fraction") presents a range of values between zero and one: values of this ratio near zero indicate that ET is significantly reduced, soil moisture is considerably depleted, and E_0 is highly elevated; values close to one indicate that ET and soil moisture are sufficient to meet the associated demand of moisture from the atmosphere. Anderson *et al.* (2007a, 2007b) use evaporative stress in their formulation of their Evaporative Stress Index (ESI). In ESI, ET is estimated from remote sensing data via the Atmospheric Land Exchange Inverse (ALEXI) model and normalized by E_0 derived from reanalysis data. This ET/E_0 fraction is standardized to produce ESI values (in units of standard deviations) that are comparable spatially and temporally. Under a different nomenclature, Christian *et al.* (2019a) designate the ET/E_0 ratio as the Evaporative Stress Ratio (ESR) and further standardize it to produce the Standardized Evaporative Stress Ratio (SESR). While the mathematical processes to produce ESI and SESR are identical, the inputs of each distinguish the two metrics. While the ESI is a satellite-derived metric, SESR is generally derived from reanalysis datasets. Numerous studies have shown that the ESI and SESR are reliable indicators of flash drought occurrence because rapid decreases in the ET/E_0 ratio, and the increasing vegetation stress that this trend represents, is a tangible impact of drought on the land surface (Anderson *et al.*, 2013; Otkin *et al.*, 2013, 2016; Christian *et al.*, 2019a; Nguyen *et al.*, 2019, 2023). In essence, potential flash drought events identified via high E_0 can be confirmed through use of ET-based indicators.

3.3 Soil Moisture Indicators

Soil moisture is a critical indicator for drought monitoring because it integrates the effects of precipitation deficit and ET, it regulates plant root water uptake, and it can affect the persistence and intensity of drought via soil moisture feedbacks (Seneviratne *et al.*, 2010). Though its monitoring has progressed rapidly in the past 10-20 years, soil moisture remains less well monitored than either precipitation or air temperature. Existing soil moisture datasets can be divided into four categories: (1) *in situ*; (2) satellite- or aircraft-based; (3) model-based; and (4) assimilated or hybrid (Brocca *et al.*, 2017). *In situ* observations are ideal for an accurate, point-based assessment of soil moisture, and are often the only source of actual soil moisture measurement. However, *in situ* observational networks are rarely of sufficient density to capture the variability of soil moisture across large spatial areas (Dorigo *et al.*, 2011). Furthermore, the accuracy of *in situ* measurements relies on proper sensor calibration, installation, and maintenance (Cosh *et al.*, 2016). Inconsistency in one or all of these important components between regional or state soil moisture networks has been a major challenge for national-scale *in situ* soil moisture monitoring (Baker *et al.*, 2022).

In situ soil moisture observations are critical for the calibration and validation of remote sensing- and model-based products, including those for flash drought monitoring (Ford & Quiring, 2019). However, the spatial representativeness has so far hindered the development of *in situ*-based soil moisture flash drought monitoring tools. Ongoing efforts toward a National Coordinated Soil Moisture Monitoring Network (Clayton *et al.*, 2019) could greatly improve coordination and resources for *in situ* soil moisture-based drought monitoring across the United States, and similar efforts are ongoing in other parts of the world (Dorigo *et al.*, 2011).

Microwave satellite remote sensing provides a spatially comprehensive and cohesive observation of soil moisture (Babaeian *et al.*, 2019), but typically can only observe the top few centimeters of the soil column (Brocca *et al.*, 2017). These surficial estimates are insufficient to represent drought in areas where surface-atmosphere energy exchange and plant water use are modulated by moisture in deeper soil layers. The FLASH product (Flash Drought Assessment using SMAP Hydrology; Sehgal *et al.*, 2021), for example, uses the Soil Moisture Active-Passive product (SMAP; Entekhabi *et al.*, 2010) to represent changes in surface soil moisture. FLASH leverages the spatial coverage and short latency of SMAP soil moisture estimates to provide global-scale flash drought monitoring. However, as with any microwave remote sensing-based product, FLASH does not capture root zone soil moisture, which can be important for vegetation and hydrology response to drought onset and intensification. Nonetheless, one of the most important benefits of satellite-based soil moisture tools is their global coverage, which facilitates its support of flash drought early warning, food-security monitoring, and decision-making in food-insecure countries, potentially as part of the Famine Early Warning System Network (FEWS NET) framework (Van Ginkel & Biradar, 2021).

Land surface models can simulate root zone soil moisture across large regions; however, like any model, they are constrained by uncertainties in model physics, parameterization, and the quality of data initialization (Ford & Quiring, 2019). Many land surface model-based soil moisture tools exist, both within the United States and globally (Xia *et al.*, 2012; McDonough *et al.*, 2018; Sadeghi *et al.*, 2020). These products have the sufficient spatial coverage, root zone estimates, and short latency to greatly benefit flash drought monitoring. The primary challenge for land surface model-based soil moisture flash drought monitoring is ensuring the model accurately represents soil moisture conditions and dynamics, especially soil wetting and drying. *In situ* soil moisture measurements are critical to improve model representation; however, the dearth of *in situ* measurements in certain landscapes such as forest, row crop, and wetlands limits land surface model accuracy for ecological and agricultural drought monitoring. Therefore, increasing *in situ* soil moisture monitoring in general and across a diversity of land uses will improve land surface model utility for pan-sector flash drought monitoring. In addition, land surface models do not incorporate human interventions such as irrigation and groundwater pumping that can impact soil moisture and flash drought occurrence. Moreover, proper representation of human-interventions that affect water and energy cycles in the land surface models is vital for their utility in flash drought monitoring and forecast.

4. FLASH DROUGHT CLIMATOLOGICAL CHARACTERISTICS

In flash drought climatology, a critical goal is to understand when and where flash droughts are mostly likely to occur. Quantifying the climatological characteristics of flash drought provides a foundation for improved monitoring and predictability through identification of seasonal and regional hotspots for flash drought development.

Several studies have been undertaken in recent years to examine the global distribution of flash drought primarily using soil moisture and evaporative stress obtained from reanalysis datasets during the satellite era (1980 to present day). While results depend to a large degree on the variables, datasets, and definitions used (Mukherjee & Mishra, 2022; Osman *et al.*, 2021), a convergence of the climatological signal of flash drought has emerged over several regions across the globe. The most consistent hotspots have been shown to occur over the Sahel and India (Christian *et al.*, 2021; Deng *et al.*, 2022; Koster *et al.*, 2019; Yuan *et al.*, 2023). Flash drought frequency is generally highest in the middle of the warm season in equatorial latitudes (Christian *et al.*, 2021; Koster *et al.*, 2019). A more prominent seasonal cycle of higher flash drought occurrence in the warm season is evident in the mid-latitudes, due to elevated evaporative demand during the summer. Mahto and Mishra (2023) reported that significant warming and decline in precipitation resulted in an increased frequency of flash droughts in the major global croplands during 1981-2020. In addition, simultaneous occurrence of flash droughts in several major croplands across the globe has also increased during the same period.

While global studies provide a high-level summary of flash drought characteristics, further details can be gleaned from regional analyses. Here, we present a regional perspective of flash drought, focusing on continents and a subset of countries in which these droughts have been studied. The subsections are presented in alphabetical order.

4.1 Africa

There are few studies of flash drought within regions of Africa. Instead, findings are mostly parsed from global studies; for example, Christian *et al.* (2021) found that flash drought occurrence is highest across Africa compared to other continents, with the most notable hotspots over the Sahel and Great Rift Valley. In a case study of a December, 2015 flash drought in southern Africa specifically in the context of anthropogenic intensification, Yuan *et al.* (2018) found that rapid drought development occurred over this region via large rainfall deficits and above-average temperatures, and was shown with a rapid decline in soil moisture. Overall, it was found that dry soils resulting from the flash drought may have contributed to record heat waves in the area. In a regional study in the Awash River basin of central Ethiopia, Getahun and Li (2023) found that flash droughts were mostly associated with agricultural crops and grasslands in the basin. Flash drought mainly occurred during the rainy seasons, with a strong sensitivity to rainy season timing, particularly of the short rains. They also found that agropastoralists were particularly vulnerable to flash droughts.

4.2 Asia

Numerous studies have examined flash drought over China (a total of 48; Table 1), including 29 that focused on their climatological characteristics. Ten of these studies quantified a climatology of flash drought across all of China, while 19 studies examined flash drought within individual basins, plateaus, or subregions, including Horqin Sandy Land (Hu *et al.*, 2023), the Huaibei Plain (Gou *et al.*, 2022), the Loess Plateau (Hu *et al.*, 2021; Zhang *et al.*, 2022b; Zheng *et al.*, 2022), the Pearl River basin (Li *et al.*, 2020a; Yang *et al.*, 2023b; Zha *et al.*, 2023; Zhong *et al.*, 2022), provinces in southern China (Li *et al.*, 2022), Xilinguole (Liu *et al.*, 2022), the Yellow River basin (Liu *et al.*, 2020b), the province of Guangxi (Yang *et al.*, 2023a; Yun-chuan *et al.*, 2023), the Hai River basin (Yao *et al.*, 2022), the Gan River basin (Zhang *et al.*, 2017; Zhang *et al.*, 2021), the Qilian Mountains (Yin *et al.*, 2023), and the Yangtze River basin (Liang *et al.*, 2023).

The climatological characteristics of flash drought over China are discussed here using papers that identify flash drought via rapid drought intensification (Fu & Wang, 2022; Gong *et al.*, 2022; Liu *et al.*, 2020a; Wang & Yuan, 2022; Xi & Yuan, 2023; Yuan *et al.*, 2019; Zhang *et al.*, 2020a; Zhang *et al.*, 2023). Yuan *et al.* (2019) was the first of these studies to quantify flash drought over China. They revealed a gradient of flash drought frequency across the country with the highest occurrence of flash drought in humid areas of southeast China, and lower in the more-arid and higher-elevation portions of northwest China. Similar results were found by Xi and Yuan (2023) and Zhang *et al.* (2023). Further, it has been found that flash droughts with the most rapid rate of intensification occur in southern China (Wang & Yuan, 2022). Liu *et al.* (2020a) found a similar but slightly modified spatial pattern, with a higher occurrence in central China, and lower over southwest and far northeast China. Most of these studies use similar variables and methodologies for identifying flash drought, thereby leading to similar conclusions (Fu & Wang, 2022; Gong *et al.*, 2022; Liu *et al.*, 2020a; Wang & Yuan, 2022; Zhang *et al.*, 2020a). Gong *et al.* (2022) found that even a small change to an identification method (e.g., changing the minimum length of flash drought from 2.5 weeks to 4 weeks) resulted in notable changes to the hotspot locations of flash drought occurrence across China.

Country-wide analysis on the seasonality of flash drought remains limited, with the exception of Gong *et al.* (2022), which noted that flash drought occurs more often in the spring and summer for northeastern and central China. Results from local-scale studies have indicated large regional differences in the relative risk of flash drought during the warm season (e.g., April to October). For example, Zhang *et al.* (2021) found that July through October had the highest flash drought occurrence for the Gan River basin in southeast China, while Gou *et al.* (2022) indicated no distinct period of higher flash drought occurrence across the Huaibei Plain in east-central China. Additionally, studies have produced different results in flash drought seasonality when using different identification methods and variables, with Hu *et al.* (2021) finding a bimodal signal in peak flash drought occurrence (May and August) over the Loess Plateau in north-central China but Zheng *et al.* (2022) finding peak flash drought occurrence in the summer over the same region. This is similar to the variability in results found with studies over the United States and on global scales (Mukherjee & Mishra, 2022; Osman *et al.*, 2021). While consistent spatial patterns of flash drought occurrence have been identified, further research is needed to identify seasonal hotspots.

A majority of studies over China have investigated flash drought events covering individual basins or plateaus. Further, in studies that explore flash drought across all of China, example years are typically used to illustrate a methodological approach without providing spatial context or associated impacts from an event (e.g., Fu & Wang, 2022; Yuan *et al.*, 2019). One study noted widespread flash drought development across China in 2006 associated with negative precipitation and positive evaporative demand anomalies; however, impacts from the event were not explored (Liu *et al.*, 2020a). Additionally, a notable contribution from smaller scale studies has included trajectory analysis by mapping the spatial evolution of flash drought development over time (Gou *et al.*, 2022; Li *et al.*, 2020b; Li *et al.*, 2022; Liang *et al.*, 2023). Overall, future opportunities exist to further identify specific and high-impact flash drought events across China.

A diverse set of datasets and indicators has identified India as a global hotspot for flash droughts (Christian *et al.*, 2021; Deng *et al.*, 2022; Koster *et al.*, 2019); however, their climatological characteristics at regional scales remain uncertain. Using the same flash drought identification framework (but with different datasets), Mahto and Mishra (2020) found that flash drought occurs most frequently in central and eastern regions of India during the summer monsoon season, while Poonia *et al.* (2022) and Rakkasagi *et al.* (2023) saw the largest frequency in western India during the monsoon season. Further, Mahto and Mishra (2020) indicate that more than 80% of flash droughts occur during the summer monsoon season, while Poonia *et al.* (2022) revealed twice as many flash droughts in the non-monsoon across India compared to the monsoon season. While using different datasets may contribute to the different results (Mukherjee & Mishra, 2022; Osman et al., 2021), further work is needed to resolve these discrepancies, specifically within the context of the climatological occurrence of flash drought across India.

While few studies have explored regional flash drought characteristics across India, some key events have been identified. The most notable includes the flash drought of 1979, which is considered to be the most severe flash drought since 1951 by spatial coverage, duration, and intensity (Mishra *et al.*, 2021). This event occurred during late August and early September, and impacted at least 40% of the country (Mahto & Mishra, 2020; Mishra *et al.*, 2021). The event primarily occurred over rice producing regions and led to significant crop losses (Mahto & Mishra, 2020; Zhang *et al.*, 2017). Other major events include 2009, which was associated with extreme temperature anomalies, and 1986, which was widespread across India and led to agricultural losses (Mahto & Mishra, 2020; Mishra *et al.*, 2021; Zhang *et al.*, 2017).

One study focused on climatological characteristics of flash drought during a 20-year period (2001-2020) over the Korean peninsula using flux tower and remote sensing observations (Kang *et al.*, 2023). It was found that the frequency of flash drought varied by land cover type and impacts on ecosystems increased as the flash drought intensification rate increased.

4.3 Australia

Interest in flash drought research over Australia has rapidly increased in recent years, with several published studies since 2019. Parker *et al.* (2021) and Nguyen *et al.* (2023) are currently the only two studies to quantify a climatology of flash drought across all of Australia. The results from these studies revealed the highest risk of flash drought occurrence across northern and eastern Australia. The regional-scale analysis of Parker *et al.* (2021) and Nguyen *et al.* (2023) also aligns with the global flash drought analyses that have highlighted northern and eastern Australia with elevated flash drought occurrence compared to the more arid central Australia (Christian *et al.*, 2021; Deng *et al.*, 2022; Mukherjee & Mishra, 2022; Qing *et al.*, 2022). Further, flash droughts were found to occur in about 25% of wet seasons when averaged across northern Australia (Lisonbee *et al.*, 2021).

A seasonality in flash drought occurrence is also evident, with the highest frequency of flash drought in the austral summer (December – February), particularly across northern Australia (Parker *et al.*, 2021; Nguyen *et al.*, 2023). The timing of peak flash drought occurrence coincides with the onset of the monsoon in northern Australia; Christian *et al.* (2021) hypothesize that a delayed onset of the monsoon may play a role in driving flash drought development during the summer. Lisonbee et al. (2021) found that while a delayed monsoon onset occasionally contributes to regional flash droughts, prolonged monsoon breaks within the season can also contribute. Flash drought case studies have focused on eastern Australia, where elevated flash drought occurrence has been identified (Parker *et al.*, 2021). These events have primarily been examined using ESI and include a flash drought event across eastern Australia between December 2017 and January 2018 (Nguyen *et al.*, 2019), an event within the Central Slopes region in June 2019 (Nguyen *et al.*, 2021), and a flash drought in eastern Australia in November of 2019. In addition, Dunne and Kuleshov (2023) found evidence for a likely flash drought event in southeastern Australia during March and April of 2019 using a monthly drought risk index. While studies have focused on the temporal and spatial evolution of the flash droughts and climatic drivers of these events, research on their associated impacts is limited.

4.4 Europe

Interest in flash drought research across Europe has increased in recent years. Two recent studies assessed flash drought over the entire European continent (Shah *et al.*, 2022; O & Park, 2023) using rapid declines in soil moisture to identify flash drought. These studies found that flash droughts occur most frequently in central and eastern Europe (Shah *et al.*, 2022; O & Park, 2023) and have become more common across all of Europe, with many areas experiencing at least an 80% increase in flash drought frequency from 1950-1984 to 1985-2019 (Shah *et al.,* 2022). Shah *et al.* (2023) also identified two types of flash drought development across Europe. The first is associated with a decline in precipitation combined with increased evaporative demand, while the second type is associated with high precipitation preceding the event start, followed by an immediate precipitation deficit. In addition to the continental flash drought studies, Spain has been the focus of two flash drought climatology studies by Noguera *et al.* (2020, 2021). Using the SPEI over a four-week period, Noguera *et al.* (2020) found that flash droughts occur most frequently in summer and that there is large spatial variability in flash drought frequency across Spain, with the highest occurrence in the northwest region of the country. They also estimated that nearly 40% of drought events in Spain develop as flash drought. Case studies of flash drought events in the Czech Republic were examined by Mozny *et al.* (2012) and across Spain by Noguera *et al.* (2022). Noguera *et al.* (2021) demonstrated that using different variables, even while employing the same identification methodology, can reveal very different results regarding the spatial and seasonal hotspots of flash drought within Spain. Alencar *et al.* (2022) used time series analysis to show how various methods and indicators result in substantial variability in flash drought timing and intensity.

Global climatological studies have not provided evidence for global hotspots of flash drought in Russia. However, a notable high-impact flash drought occurred in southwestern Russia during 2010 (Christian *et al.*, 2020). Rapid land surface desiccation in June supplemented the development of an extreme heatwave by late July and early August across the region. The flash drought was associated with cascading agricultural and socioeconomic impacts, which ultimately led to global-scale impacts on wheat prices (Hunt *et al.*, 2021).

4.5 North America

The United States is tied with China as the most heavily studied region with respect to flash drought, with at least 11 studies dedicated to quantifying the climatological characteristics of flash drought and an additional 37 studies exploring topics pertaining to flash drought (Table 1). Similar to caveats associated with global-scale flash drought analysis, large variability can exist between climatological studies, with differences attributed to the flash drought identification method and the variables and dataset used for analysis (Osman *et al.,* 2021). However, studies have consistently shown the highest frequency of flash drought over central CONUS (Chen *et al.*, 2019; Christian *et al.*, 2019a; Lesinger & Tian, 2022; Osman *et al.*, 2022), most frequently in the middle of the warm season, due to increased evaporative demand and vegetation water requirements (Chen *et al.*, 2019; Christian *et al.*, 2019b; Otkin *et al.*, 2021). CONUS-wide, the peak timing for flash drought occurrence varies, with flash droughts more likely in the spring and early summer in the west, and more likely in the fall for the east (Christian *et al.*, 2019b; Otkin *et al.*, 2021).

Using rapid intensification derived from the USDM (2000-2019), flash droughts have been estimated to comprise 10% of all drought development in the United States (Leeper *et al.*, 2022). In addition, it has been found that approximately 37-49% of flash droughts persist to become long-term droughts, depending on the region within the United States (Christian *et al.*, 2019b). Edris *et al.* (2023) found that the climate in the western United States allows for relatively short and rapid dry down periods, but that few of these events classify as flash droughts because rapid transitions are a normal part of the climate system in this region. Further, Osman *et al.* (2022) categorized flash drought into three distinct classes, and discovered that 1) flash droughts defined primarily with a precipitation deficit occur most often across the western High Plains of the United States, 2) flash droughts that are primarily evaporative driven are most common in the upper Midwest, and 3) flash drought events that are both “dry and demanding” are most common across the southern Great Plains.

A flash drought that occurred in 2012 across the central United States has been extensively studied from the perspective of its spatial and temporal evolution (Basara *et al.*, 2019; Otkin *et al.*, 2016), predictability (DeAngelis *et al.*, 2020; Liang & Yuan, 2021), and impacts on agriculture and ecosystems (Jin *et al.*, 2019). The attention within the scientific literature on this event is closely followed by the 2017 flash drought across the Northern Great Plains, which led to a significant decrease in crop production and an increased risk for wildfire development (He *et al.*, 2019). Additional flash drought events with dedicated studies include the flash drought-flash recovery sequence over the south-central United States in 2015 (Otkin *et al.*, 2019), stakeholder response to flash drought during 2016 in the Northern Great Plains (Otkin *et al.*, 2018b; Haigh *et al.*, 2019), and the 2019 flash drought in the southeast United States and associated relationship with teleconnections (Schubert *et al.*, 2021).

4.6 South America

Brazil has been identified as a global flash drought hotspot (Christian *et al.*, 2021; Deng *et al.*, 2022; Mukherjee & Mishra, 2022a). Anderson *et al.* (2016) highlighted the use of ESI as an agricultural drought indicator, inferring a few notable flash droughts via rapid declines in ESI. Flash drought events were identified in 2009 and 2012 in southern Brazil, as well as mid-2011 and mid-2012 in northeast Brazil. These flash drought events were found to significantly reduce corn yields.

Table 1. Number of flash drought studies partitioned by country, region, or global focus that have been published as of August 2023.

Country-Specific Studies		Multi-country Studies		Global Studies
China	48	Europe	4	17
United States	48	Korean Peninsula	1	
Australia	6	Southern Africa	1	
India	4			
Spain	4			
Russia	2			
Brazil	1			
Czech Republic	1			
Ethiopia	1			

5. ATMOSPHERIC AND OCEANIC DRIVERS OF FLASH DROUGHT

Atmospheric and oceanic features associated with flash droughts have been identified based on individual case studies and generalized studies of many flash droughts occurring in a given region and season. Flash droughts are related to stationary atmospheric Rossby waves, viewed as sequential high and low pressure areas, that lead to persistent high pressure and conditions conducive for flash drought (Christian *et al.*, 2020; Hoerling *et al.*, 2014). Stationary Rossby waves may be generated internally by the atmosphere or affected by other features in the earth system like the El Nino-Southern Oscillation (ENSO; Wang *et al.*, 2017a) and the Indian Ocean Dipole (IOD; Saji *et al.*, 1999). However, considerable knowledge gaps remain regarding remote flash drought drivers. These knowledge gaps are related to the infrequency and regionality of these events (Christian *et al.*, 2019b), and that the behaviors of potential drivers may vary between seasons, including features of the atmosphere (e.g., Newman & Sardeshmukh, 1998; Breeden *et al.*, 2021) and climate modes that may force the atmosphere like ENSO (e.g., Jong *et al.*, 2020). The lessons learned from these studies may be used to forewarn of future flash droughts, thereby enabling early action that lessens the negative effects of these events (Otkin *et al.*, 2022). The predictive information provided by atmospheric and oceanic features regarding flash drought depends on whether these features and their compounding and cascading effects are predictable and at what lead times.

Case studies of individual flash droughts have been the primary lens to study the atmospheric features related to such events, with fewer studies generalizing atmospheric features across many events (Jong *et al.*, 2022). Case studies that have noted the effects of stationary Rossby waves on flash droughts have focused on some of the largest and most impactful events, such as those that occurred in the United States in 1980, 1988, 2012, and 2017 (e.g., Table 1 in Jong *et al.*, 2022 and references therein), and 2010 in Russia (Dole *et al.*, 2011; Christian *et al.*, 2020). As highlighted by the 2010 flash drought in Russia, subsidence from an area of upper-level atmospheric high pressure acts to suppress the development of precipitation as well as increase evaporative demand at the land surface (Christian et al. 2020). The combination of a lack of precipitation and enhanced evaporative demand are key drivers in the development of flash drought (Otkin *et al.*, 2013). Concerning the aforementioned United States flash droughts, the characteristics of stationary Rossby waves related to them are unique to each event. Rossby waves during the 1988 (Mo *et al.*, 1991; Chen & Newman, 1998; Wang *et al.*, 2017b) and 2012 (Hoerling *et al.*, 2014; Wang *et al.*, 2014; PaiMazumder & Done, 2016; Basara *et al.*, 2019; DeAngelis *et al.*, 2020) flash droughts led to expansive and persistent high pressure over the United States and permitted the large spatial footprint of rapid drought onset. Rossby waves during the 1980 (Karl & Quayle, 1981; Namias, 1982; Lyon & Dole, 1995) and 2017 (Wang *et al.*, 2019) flash droughts led to more regionally confined high pressure centers, with the former affecting the Southern Plains and the latter the Northern Plains. Generalizable atmospheric features related to flash droughts have focused on specific regions and seasons, highlighting the effect of stationary Rossby waves dependent on the particular selection criteria. Examples include the eastern United States (Ford & Labosier, 2017), East Asia (Bollasina & Messori, 2018), and the central and northern Great Plains in the United States (Jong *et al.*, 2022).

ENSO and IOD have been linked to flash droughts in certain regions and seasons, as these aspects of weather and climate variability perturb the atmosphere and force stationary Rossby waves that lead to flash drought in remote locations. Examples of ENSO-affected regions as documented in the flash drought literature are: the United States (Chen *et al.*, 2019), Australia (Nguyen *et al.*, 2020), and Southern Africa (Yuan *et al.*, 2018). Though evidence suggests that ENSO broadly affects flash drought in the United States, this may not be the case for given events. For example, some studies have argued that the La Niña phase of ENSO played a key role in the 1988 flash drought over the United States (Trenberth *et al.*, 1988; Trenberth & Branstator, 1992; Atlas *et al.*, 1993) while others have argued that its effect on this flash drought was secondary (e.g., Mo *et al.*, 1991; Chen & Newman, 1998). The IOD is linked to flash droughts in Australia (Nguyen et al., 2021) and the southeastern United States (Schubert *et al.*, 2021), as indicated by its effect on simultaneous flash droughts in both regions during autumn of 2019.

6. FLASH DROUGHT FORECASTING

6.1 Subseasonal-to-Seasonal Prediction

Skillful and reliable flash drought forecasts on subseasonal-to-seasonal (S2S) timescales are essential for preparing for and mitigating flash drought impacts. Dynamical models have been used as a primary tool for this purpose (DeAngelis *et al.*, 2020; Hoell *et al.*, 2019a, 2019b, 2020; Mo & Lettenmaier, 2020; Liang & Yuan, 2021; Lesinger *et al.*, 2023; Ma & Yuan, 2023). However, skillful and reliable forecasts have been challenging to achieve, given that forecast skill is often limited to lead times of 1-3 weeks and depend on indicator, region, season, forecast model, and initial land state. For example, soil moisture is considerably more predictable than ESI in their rapid temporal changes (Lorenz *et al.*, 2021); atmospheric evaporative demand indicators (e.g., reference evapotranspiration) are more skillfully forecast than precipitation (McEvoy *et al.*, 2016b); the 2017 U.S. High Plains flash drought has no forecast skill in S2S dynamical forecasts (e.g., GEFS, NMME; Hoell *et al.*, 2019a, 2019b, 2020), whereas the 2012 U.S. Great Plains flash drought can be predicted at the lead time of two weeks in SubX, except for a few initialization dates when the skill can extend to 3-4 weeks (DeAngelis *et al.*, 2020). To improve flash drought forecast skill and complement dynamical forecasting systems, statistical and hybrid statistical-dynamical prediction models have been developed. In these models, linear regression and more advanced nonlinear machine learning (ML) and deep learning (DL) methods were applied to account for the dependence of flash drought predictands on predictors drawing from observed current and past atmospheric and land surface states, S2S dynamical forecasts, and potential sources of flash drought predictability (e.g., ENSO, MJO; Lorenz *et al.*, 2017, 2018, 2021, 2023; Tyagi *et al.*, 2022). Results show considerable skill improvement for the lead times of up to 4 weeks, where land initial state is the dominant contributor with dynamical forecasts playing a secondary contributing role, suggesting the importance of improving land initialization in dynamical forecasting systems. Additionally, monitoring information can be essential to flash drought early warning when dynamical and statistical forecasts provide little skill.

Examples include atmospheric evaporative demand indices (e.g., ESI, EDDI) and their rapid temporal changes (Otkin *et al.*, 2013, 2014, 2015a; Hobbins *et al.*, 2016; Chen *et al.*, 2020; Mohammadi *et al.*, 2022).

The limited forecast skill of flash drought is attributable to not only the limited predictability of flash drought but also deficiencies in the forecast tools used. The latter can be exemplified by the inadequate representation of two identified sources of flash drought prediction skill: stationary Rossby waves and realistic land initialization (Wang *et al.*, 2017b; DeAngelis *et al.*, 2020). An accurate prediction of stationary Rossby waves and their effects on flash drought development would require forecast models to capture the sources of the waves, accurately simulate subtropical mean jets (location, shape, and magnitude) that guide the wave propagation, and properly simulate cloud and precipitation processes in the flash drought regions. The latter is needed for accurately translating the effects of arriving stationary Rossby waves into local precipitation deficits and above-average atmospheric evaporative demand that subsequently drive flash drought. However, current climate models have a variety of warm-season biases that hinder a proper simulation and prediction of these processes (e.g., Morcrette *et al.* 2018; Chang *et al.* 2019). These model biases include convective biases in the tropics and subtropics, stunted Northern Hemisphere jets (Harvey *et al.*, 2020), and precipitation and temperature biases in the land regions (e.g., warm and dry biases in the central U.S.; Lin *et al.*, 2017). Chang *et al.* (2019) made an effort to remove much of these model biases by applying empirical short-term (6-hourly) atmospheric tendency bias correction during the forecast integration. However, the improvement is modest in S2S prediction of stationary Rossby waves and their associated anomalies in surface temperature, and is insignificant in that of precipitation. Chang *et al.* (2019) presume that this is due to the time competition between the predictability limit of stationary Rossby waves and the time it takes for correcting model biases and remedying climate drift to start having a notable positive impact on the forecast skill. Similarly, current operational forecasting systems may not have accurate land initializations. These forecast systems usually obtain their initial land surface states from the land component of an existing reanalysis (e.g., Hamill *et al.*, 2022). The accuracy of their land initializations is thus subject to the performance of the land Data Assimilation System (DAS) in the reanalysis. The specific influencing factors include the performance or quality of land DAS components: land data assimilation schemes, assimilated ground- and space-based observing systems, and land surface models and their input atmospheric forcings, particularly precipitation. The land initialization can be adversely affected by any issues in the above factors; it likewise can be improved by enhancing any of these factors.

6.2 Flash Drought in a Changing Climate

Analysis of both historical data and model projections, globally and regionally, largely find trends toward increasing flash drought frequency (Yuan *et al.*, 2019; Christian *et al.*, 2021; Sreeparvathy & Srinivas, 2022; Mahto & Mishra, 2023). These broader trends are attributed, in part, to anthropogenic climate change, as well as consistent projected increases in evaporative demand combined with variable, but mostly small, projected changes in global precipitation (Yuan *et al.*, 2019; Mishra *et al.*, 2021; Noguera *et al.*, 2022; Christian *et al.*, 2021; Yuan *et al.*, 2023). For example, Mishra *et al.* (2021) attributed the projected increased flash drought frequency in India to increased intraseasonal variability of the monsoon, with increased flash drought risk following failed or delayed monsoon onset. Kang *et al.* (2022) found similar results for the Mekong River Basin in southeast Asia. In contrast, projected increasing flash drought frequency in parts of North America are attributed to large increases in evaporative demand relative to modest increases in both total precipitation and precipitation variability (Hoffman *et al.*, 2021; Christian *et al.*, 2023). These regional drivers of flash drought are important factors when determining the regional prognosis of flash drought impacts with continued climate change. Beyond frequency of occurrence, studies have found observed and projected increases in flash drought severity, duration, and spatial extent in many regions (Sreeparvathy & Srinivas, 2022; Shah *et al.*, 2022; Yuan *et al.*, 2023). However, it is important to note that flash drought projections vary substantially across regions, models, and metrics, and these differences–placed in the context of future climate uncertainty–raise important questions to be addressed by further research.

Among the most important confounding factors for accurate and actionable future flash drought information are the complex interactions between meteorological flash drought drivers and the hydrological response. Most studies characterizing potential future flash drought conditions do so using soil moisture, precipitation, evaporative demand or evapotranspiration (Hoffman *et al.*, 2021; Yuan *et al.*, 2023; Christian *et al.*, 2023). However, the response of streamflow, groundwater, and reservoir storage to concurrent or compounding changes in precipitation and evaporative demand tend to be nonlinear, and are themselves nonstationary (Zha *et al.*, 2023). These factors challenge our understanding of how projected changes in meteorological drought translate to changes in agricultural or hydrological drought, and make it difficult to infer changes in one type of drought from projected changes in another (Hoffman *et al.*, 2021).

The seasonality of both hydrological response to and water resource impacts from flash drought create further complications. Recent studies have attempted to close this gap by coupling global climate model projections with land surface model simulations of soil moisture or streamflow, suggesting the increased evaporative demand and precipitation variability translate into more frequent or more rapid soil moisture flash droughts (Qing *et al.*, 2022; Yuan *et al.*, 2023). Nevertheless, flash drought frequency is sensitive to the extent to which precipitation is projected to change, and larger increases somewhat mitigate the effects of increased evaporative demand (Kang *et al.*, 2022). This effect may contribute to a smaller magnitude change in flash drought frequency under the highest emission scenarios relative to moderate or low scenarios (Christian *et al.*, 2023), because the former tends to produce the largest increase in precipitation in many regions by the late 21st Century. Therefore, our understanding of future flash drought changes will improve with continued improvements in precipitation modeling and through constraining uncertainty in precipitation projections. Additionally, more integrative future climate assessments will help refine our understanding of how flash drought may change in coming decades. Ideally, these would include assessment of future soil moisture, streamflow, reservoir storage, or similar, and more detailed regional attribution of flash drought conditions to meteorological drivers and compound extremes.

7. THE CHALLENGE OF DETERMINING WHEN, WHOM AND WHERE FLASH DROUGHT IMPACTS HUMAN COMMUNITIES

Empirical social science research on flash drought to date is limited and has primarily focused on U.S. agricultural producers (e.g., Otkin *et al.*, 2015b, 2018b; Haigh *et al.*, 2019, 2022). Combining these studies with insights from the wider social science of conventional drought literature reveals that the same drought event will be experienced, and likely will be perceived differently, by individuals, households, firms, or communities depending on a range of social, economic, and institutional factors (e.g., Savelli *et al.*, 2022; Cravens *et al.*, 2021a; Cravens *et al.*, 2021b; Kohl & Knox, 2016).

In their typology of drought decision making, Cravens *et al.* (2021a) describe the important relationship between the way a drought problem is framed, the way impacts or consequences are understood, and the preparedness or response options that might be selected. In the case of flash drought, one key question is whether those affected frame the drought event as flash drought or not. In some cases, conditions that satisfy the principles of flash drought (or, in the case of a case study, meet the technical criteria defined therein; see Section 2) may be perceived by those on the ground as substantially different from other drought events. In these cases, naming the event as "flash drought" may be useful. However, in other cases where an event satisfies the flash drought principles, those affected may understand the event as indistinguishable from a conventional drought event. In this situation, there may be less need, or it may even be confusing, to focus on the flash drought nature of the event. An additional challenge is that diverse definitions of flash drought exist among practitioners, complicating the ability to tease out whether perceptions or differing definitions are shaping views.

A second key question is to ask who within a region or community is affected by a flash drought event. Measuring—and ultimately predicting—flash drought impacts thus requires consideration of the component factors that derive vulnerability (Thomas *et al.*, 2019; Savelli *et al.*, 2022). Climate vulnerability, defined as "the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change" (IPCC, 2007), is a function of a system's exposure to a hazard, sensitivity, and adaptive capacity. As defined by Adger (2006, pg 270), exposure is ''the nature and degree to which a system experiences environmental or socio-political stress,'' sensitivity is the "degree to which a system is modified or affected by [climate-related] perturbations," and adaptive capacity is ''the ability of a system to evolve in order to accommodate environmental hazards or policy change and to expand the range of variability with which it can cope.'' In a population experiencing the same exposure to a flash drought hazard, differences in sensitivity and adaptive capacity explain why people experience differential impacts.

Conventional drought research tends to focus on the sensitivity of rural-, agricultural-, and ranching-dominated landscapes (Savelli *et al.*, 2022); this has similarly been the predominant focus of flash drought research to date (Otkin *et al.*, 2022). In general, agriculture is a highly sensitive sector due to direct links between water inputs and productivity, and the impact from reduced soil moisture on vegetation health tends to appear early in drought events (Wilhite *et al.*, 2007; Hobbins *et al.*, 2017), though individual agricultural producers will be more or less susceptible to drought events depending on specifics of their operation, including crop type, irrigation capacity, seniority of water rights, water conservation strategies adopted, and so on (Savelli *et al.*, 2022; Savari *et al.*, 2022). The timing of flash drought intensification interacts with these characteristics to determine impacts, too, with early season events causing significant impacts to agricultural productivity (Jin *et al.*, 2019; Otkin *et al.*, 2022).

Non-urban areas that offer outdoor recreation and tourism can also be highly sensitive to flash drought due to hydrologic and ecological drought impacts (e.g., reduced water levels in rivers or lakes, reduced food for wildlife, destruction of habitats), reducing opportunities for boating, fishing, hunting or wildlife viewing. For instance, over the course of three months, the 2017 flash drought in the U.S. northern Great Plains, and associated wildfires, resulted in a $240.5 million loss in visitor spending for Montana's tourism industry (Jencso *et al.*, 2019).

Urban areas are not immune to droughts and can be susceptible to increased pressure on municipal water suppliers (Dilling *et al.*, 2019) and health and labor impacts for urban residents (Desbureaux & Rodella, 2019). Urban areas largely supported by hydropower, nuclear or coal-fired power may also be at risk of energy supply disruptions (Desbureaux & Rodella, 2019). At the individual level, access to services, such as a central water provider (versus well-dependent households), and characteristics such as employment sector, pre-existing health conditions, number of dependents, education and occupational training obtained, and wealth or debt levels can influence sensitivity to conventional drought, and ultimately lead to a degree of flexibility when faced with uncertainty (Iglesias *et al.*, 2009; Lester *et al.*, 2022; Naumann *et al.*, 2014, 2018). In the case of flash drought, it is likely that smaller municipalities, or those with less certain water supplies or less storage would be more sensitive to flash droughts.

Additionally, trees and forest ecosystems provide important environmental mitigation effects in urban areas around the world, including reducing heat stress to residents and city infrastructure, removing nutrient pollution from stormwater, improving air quality, sequestering carbon, reducing runoff surges and associated flash flooding during heavy rainfall events, and improving physical and emotional health of urban residents (Beyer *et al.*, 2014; Gillner *et al.*, 2015; Willis & Petrokofsky, 2017; Zhang *et al.*, 2020b). Drought is a significant stressor to urban trees and can decimate the urban canopy without proper management ahead of, during, and after a drought event. Drought can set off a cascade of impacts, including increased insect pest stress and less effective ecosystem services (Frank, 2021; Allen *et al.*, 2021). Flash drought exacerbates these issues by compressing the response and mitigation timelines, which are particularly problematic in many large cities with minimal resources for watering and other tree care. Improvements in flash drought prediction, early warning, and communication can help reduce flash drought impacts to urban trees, and help maximize benefits of urban greening to the shared health of humans, plants, animals, and their environment (Felappi *et al.*, 2020).

Planning for flash and conventional drought, mitigation efforts and recovery programs can help increase a population's ability to adapt or cope with impacts, though doing so may be more difficult for flash droughts due to forecasting challenges and the rapid emergence of impacts. In an assessment of cost-effective drought planning strategies, Zaniolo *et al.* (2023) found that coping with short, intense droughts requires multiple pre-developed technologies (e.g., desalinization, potable and non-potable reuse technologies) already in existence and deployable in order to cope with potential impacts (Zaniolo *et al.,* 2023). Zaniolo *et al.* (2023) estimated that preparing for short intense drought costs as much as four times greater than the planning strategy cost for mild long-term droughts. Although Zaniolo *et al.* (2023) were discussing short, intense droughts (as distinct from flash droughts, which have no length criterion), this study suggests that coping with rapid intensification could potentially lead to much higher preparedness costs. Reactive drought responses are also common, particularly in the agricultural sector (e.g., emergency loans to producers, compensation for losses, famine relief, etc.; FAO, 2019; Moore & McEvoy, 2022); such programs may or may not be designed to adequately respond to flash drought.

8. COMPOUND AND CASCADING IMPACTS OF FLASH DROUGHT

The rapid intensification of flash droughts can result in greater sensitivity and less adaptive capacity for response. In many cases, flash droughts are expected to have greater social and economic impacts than traditional droughts due to their rapid development. This can leave less time for communities to prepare. At the same time, the compounding climate impact drivers that can accompany reduced precipitation, such as extreme heat and high winds, may also result in more severe impacts that are harder to prepare for (Otkin *et al.*, 2022; Pendergrass *et al.*, 2020; Walker &

Loon, 2023; Yuan *et al.*, 2023). Additionally, the rapid emergence of flash droughts and the difficulty of predicting them may add greater uncertainty to management efforts. For instance, in a study of municipal drought planning in California, Zaniolo *et al.* (2023) found that preparing and responding to short intense droughts was more challenging than milder, longer droughts because of the difficulty of coping with significant impacts in an accelerated timeframe and with little lead time.

Flash droughts have been associated with an elevated risk of cascading hazard events that may occur during or post-flash drought (Zscheischler *et al.*, 2018). In the short term, there is often an increased risk of wildfire (Case & Zavodsky, 2018; Hoell *et al.*, 2020), due both to the effects of hotter and drier air masses enhanced by land-atmosphere feedbacks and to increased dead fuel loads (e.g., McEvoy *et al.*, 2019; Wang and Yuan, 2022). Heat wave risk is also elevated in drier air masses (Christian *et al.*, 2020; Zhang *et al.*, 2023; Zhou & Yuan 2023)–often with dramatic effects on the mortality of human and animal populations. Longer-term effects will vary according to land cover type (Chen *et al.*, 2021; Lowman *et al.*, 2023), but extend to both the agricultural and natural systems, with agricultural yield losses (Jin *et al.*, 2019; Hunt *et al.*, 2014; Otkin *et al.*, 2016, 2018b; Kimball *et al.*, 2019) in the case of the former and a decline in ecosystem productivity (Zhang *et al.*, 2020a; He *et al.,* 2019; Yao *et al.*, 2022) in the latter.

While there have been many studies advancing flash drought detection methods and mapping flash drought occurrence globally (e.g., Christian *et al.*, 2021; Lesinger & Tian, 2022; Qing *et al.*, 2022; Yuan *et al.*, 2023), much less empirical evidence has been collected on the interacting impacts of flash droughts on social systems (Otkin *et al.*, 2022; Bachmair *et al.*, 2016; Walker & Loon, 2023). Direct impacts of conventional drought can include reduced water levels, soil moisture, vegetation health and productivity, all of which can lead to cascading indirect social and economic impacts, which are buffered or exacerbated by a population's or an individual's sensitivity (Wilhite *et al.*, 2007; Kohl & Knox, 2016; Savelli *et al.*, 2022). For example, a farm owner may experience economic impacts from reduced crop yield, leading to the inability to afford laborers, resulting in increased unemployment rates and less expendable income for other individuals in the community, and ultimately less business at local establishments (Lester *et al.*, 2022). Other economic impacts may result from the financial burden to adaptation costs, such as purchasing alternative water sources or new seeds due to lost crops (Wilhite *et al.*, 2007). In the case of flash drought, the need to adapt quickly may increase the transaction cost of doing so or make certain options infeasible. Individual or collective decision making may also become more difficult, if uncertainty about how severe a flash drought will be leads to a tendency for wait-and-see decisions (Cravens *et al.*, 2021a; Riebsame, 1990).

There is also significant work describing how conventional droughts can result in physical and mental health impacts (Bell *et al.*, 2023), including increased mortality that can vary significantly by socioeconomic strata, race, gender, age, and urbanicity (Abadi *et al.*, 2022). Physical health risks can result from increased dust and particulate matter circulating with high winds, decreased hygiene standards due to reduced water availability, or increases in pathogens from stagnant water (Vins *et al.*, 2015; Sugg *et al.*, 2020). Food insecurity and malnutrition can also increase during drought events (Hunt *et al.*, 2021; Sugg *et al.*, 2020); in some parts of the world, this can mean famine (UNDRR, 2021). Often it is young, elderly, and low-income populations who are most susceptible to health risks (Sugg *et al.*, 2020). In the case of flash drought, the rapid onset of drought conditions can result in rapid changes in food insecurity across populations or regions, especially as some parts of the world that are most vulnerable to flash drought are the same locations with limited capacity to both forecast and to prepare for or respond to flash droughts (e.g., Getahun & Li, 2023).

Mental health impacts, such as anxiety and depression, can result from financial stress or witnessing ecological degradation (Vins *et al.*, 2015). Other documented social impacts of droughts include forced migration due to loss of employment or business failure leading to a loss of sense of place, changes in family dynamics due to loss of income and laborers or requiring children or women working on the farm or in family owned business, and increases in violence due to high stress from financial hardship (Vins *et al.*, 2015; Lester *et al.*, 2022). In the case of flash drought, such mental health or social impacts may be buffered if individuals or communities have plans or resources in place to rapidly respond, or exacerbated if the rapid intensification of the event takes people by surprise.

9. FUTURE DIRECTION OF RESEARCH

Flash drought is a complex subseasonal phenomenon due to its drivers, development, and impacts. While a rapid increase in research on the topic in recent years has addressed many key knowledge gaps, many critical research questions still remain. The basis of flash drought has been centralized on the three components of rapid onset, drought development, and associated impacts. Due to complexity of the phenomenon, we suggest that the research community resists calls from practitioners for a strict, comprehensive definition of flash drought. Instead, studies should use definitions that adhere to foundational principles relating to each component of flash drought (Figure 1; Otkin *et al.*, 2018a, 2022). These study-specific definitions must balance their assessment of these components such that they remain sufficiently objective with regard to celerity and dryness and not over-emphasize observations of impacts. Flash-drought definitions that are based on observed impacts or subjective input risk over-diagnosing flash droughts: such definitions may miss the objective signals of a conventional drought onset and lead practitioners to identify what now appears as a rapid onset of impacts as a flash drought. This is especially the case if the definition of flash drought relies on impacts or on monitors such as the USDM, as in the operational definition suggested by Pendergrass *et al.* (2020).

Use of specific definitions in research and applications of flash drought should include intensive evaluation and sensitivity analyses to reduce uncertainty. Furthermore, additional research to provide intercomparisons of flash drought indicators will help determine optimal use of indicators in given regions. As an example, if indices developed for monitoring conventional drought are to be adapted for flash drought monitoring, they must control for the natural variability in the index and thereby avoid false alarms; we suggest standardizing changes in the metric, such as in the approach developed by Christian *et al.* (2019a) for the SESR metric. It is also critical for future studies to incorporate multiple indicators. An opportunity exists for research into hydrologically holistic flash drought indicators (e.g., precipitation-ET) that permit decomposition of the drivers of supply (precipitation) and demand (ET and/or E_0) within a given drought index. Further understanding into optimal flash drought approaches and indicators will provide the groundwork to develop a robust and comprehensive near-real time monitoring system of flash drought development.

Despite significant progress in research into the climatological aspects of flash drought, many regions around the world still lack information on fundamental characteristics of flash drought climatology. Similarly, more analysis would further our understanding of flash drought development and associated impacts. Further developing a catalog of flash drought hotspots and events would provide a basis for investigating the primary drivers of flash drought development. Concurrently, there is a need to better understand the sensitivity of such flash drought inventories to the indicators, dataset, and methods on which they are based. While a general understanding of atmospheric and oceanic drivers is known for select regions and seasons, there is an opportunity to improve knowledge in this topic area. Limited studies also exist on the role of land-atmosphere coupling as a driving mechanism of flash drought. Additionally, predictions of flash drought can be improved by advancing dynamical forecast systems through reduced model bias, increased accuracy of land initializations, and improved representation of physical processes (e.g., dynamic vegetation) in land surface models; statistical prediction models (e.g., Wang *et al*., 2023) are also critically needed to complement dynamical forecast systems by capturing missing predictive information therein. Furthermore, new approaches will be required to skillfully apply forecasts for various flash drought indices to flash drought prediction at S2S lead times.

Finally, social science and impact-focused analysis associated with flash drought development remains a critical focus area. While social science research is currently limited, there is an opportunity to better identify which impacts will become exacerbated with rapid-onset droughts, which populations and regions might be most sensitive to flash drought development, and what mitigation strategies are most effective for addressing impacts. Key impacts of flash droughts are well documented (agriculture yield loss, ecosystem degradation, increased wildfire risk), but there is still a need to untangle the relationship between the timing of development and cascading socioeconomic impacts.

As with slower-evolving drought, the practical importance of flash drought is in its socioeconomic and environmental impacts. The science of understanding, monitoring, and communicating flash drought impacts is rapidly evolving, and these advances will benefit the usability and effectiveness of flash drought projections for preparation and resilience planning. More research is needed to translate global- or regional-scale projections of changing flash drought characteristics to a common, impact-focused framework that can be better adopted by stakeholders and decision makers. As highlighted by Otkin *et al.* (2022), this framework requires impact assessments and scenario developments of how changing flash drought characteristics interact with the highly interconnected systems within a region. With this framework, scientists and stakeholders can also work through the uncertainty inherent in climate projections of extreme events like flash drought, to co-produce the most sustainable plan for adapting to a changing flash drought outlook and mitigating the effects of future flash drought events.

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Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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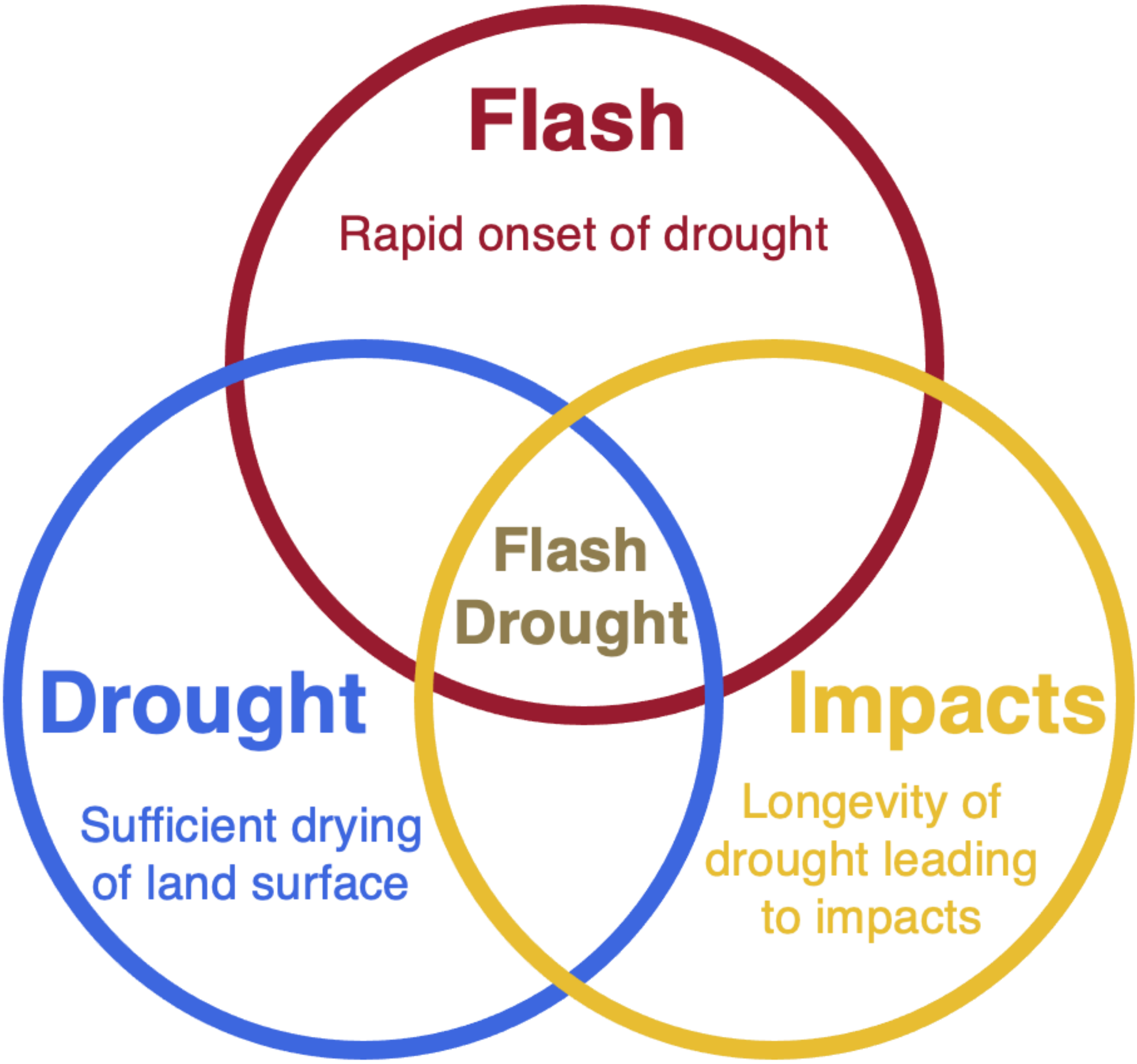

Flash
Rapid onset of drought
Flash Drought
Drought
Sufficient drying of land surface
Impacts
Longevity of drought leading to impacts

Fig. 1.tif

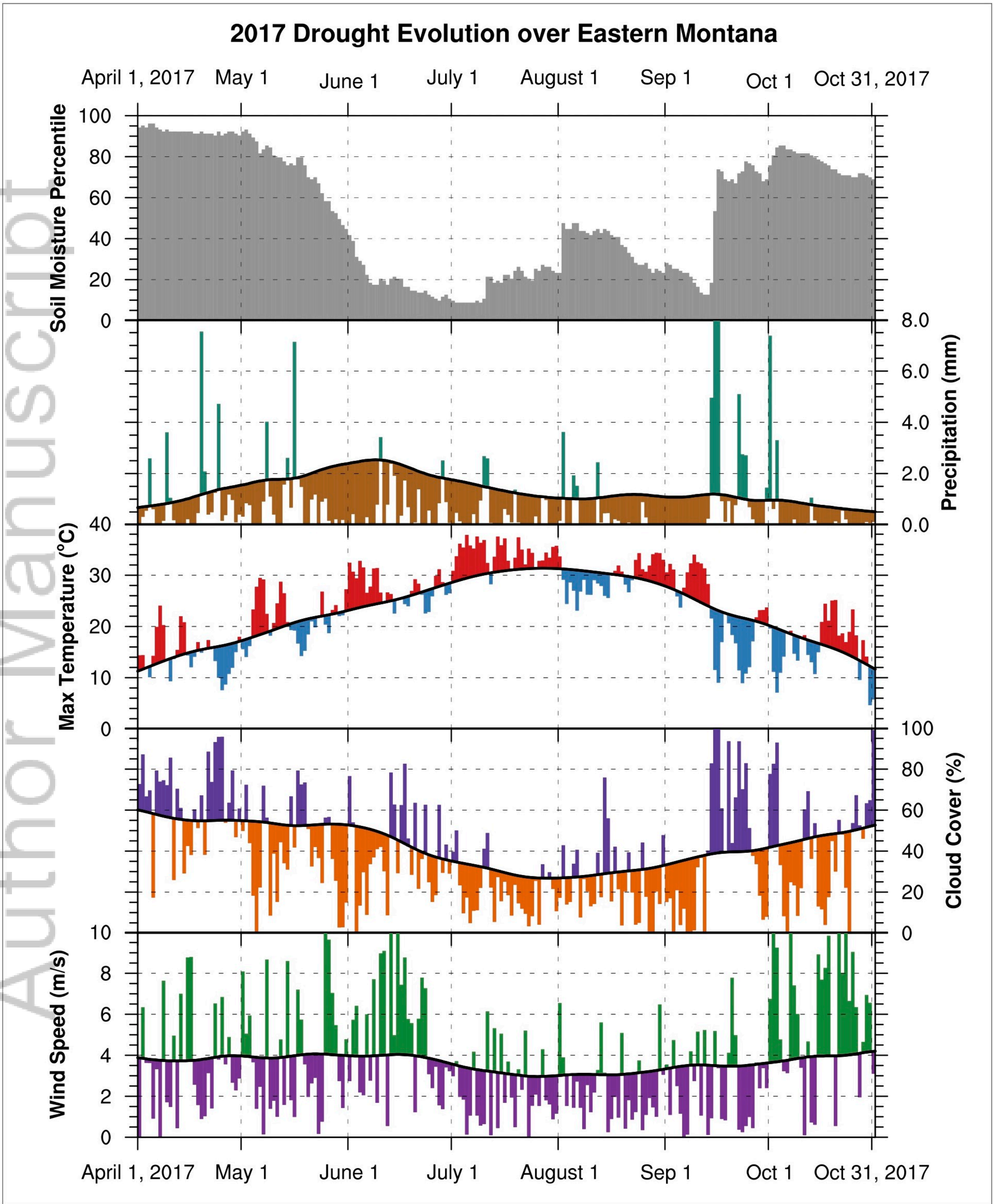
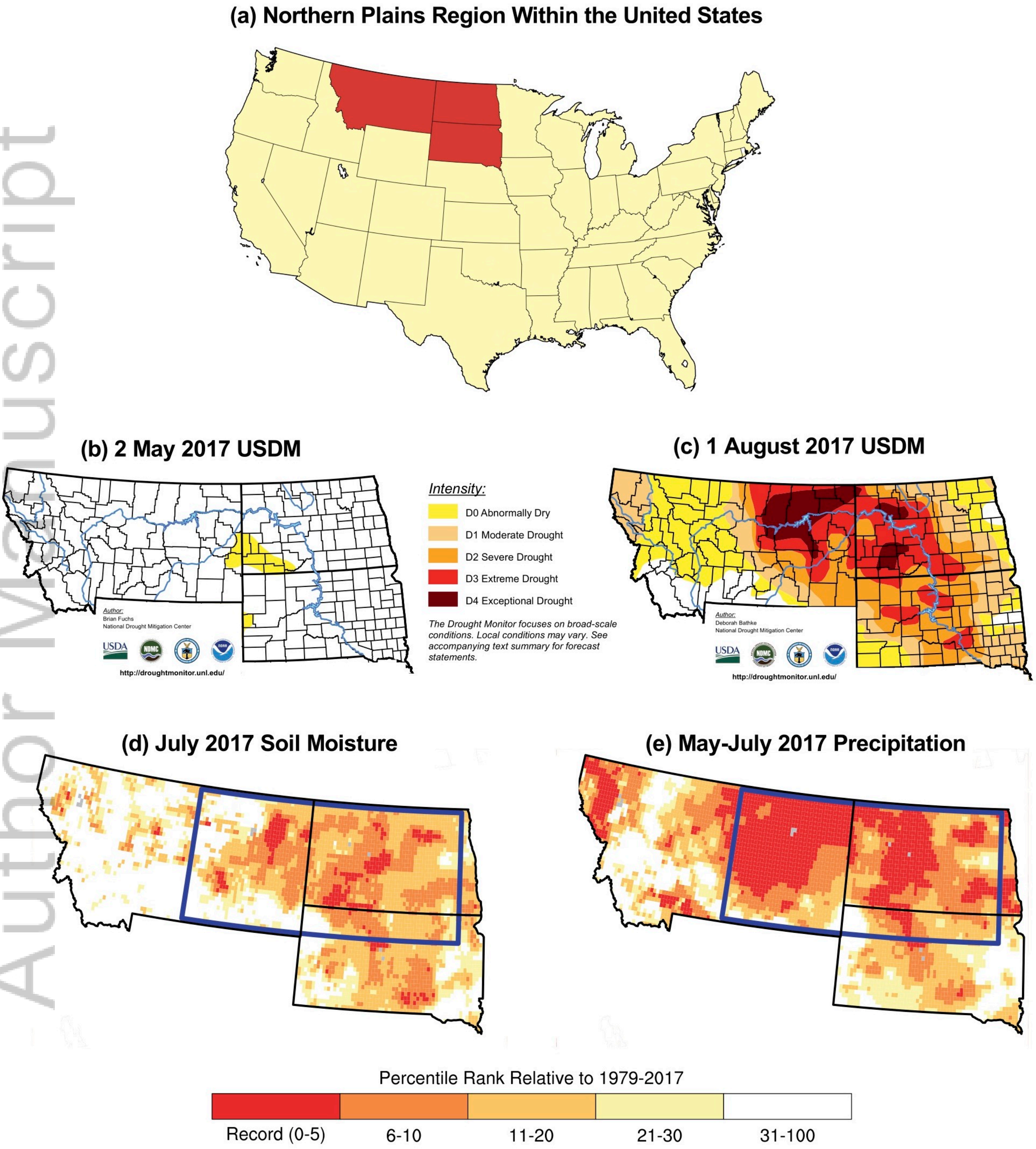
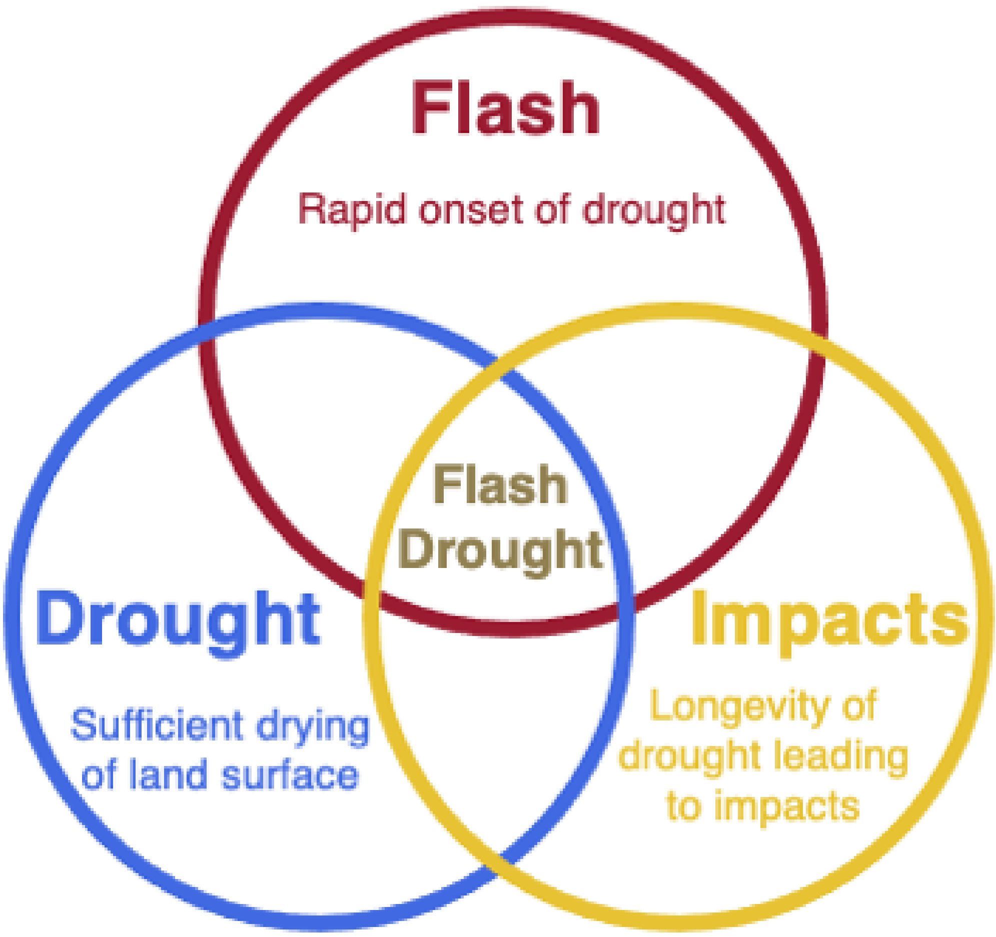

2017 Drought Evolution over Eastern Montana
April 1, 2017
May 1
June 1
July 1
August 1
Sep 1
Oct 1
Oct 31, 2017
Soil Moisture Percentile
100
80
60
40
20
0
Precipitation (mm)
8.0
6.0
4.0
2.0
0.0
Max Temperature (°C)
40
30
20
10
0
Cloud Cover (%)
100
80
60
40
20
0
Wind Speed (m/s)
10
8
6
4
2
0

Fig. 2.tif



(a) Northern Plains Region Within the United States
(b) 2 May 2017 USDM
Author:
Brian Fuchs
National Drought Mitigation Center
USDA
NDMC
http://droughtmonitor.unl.edu/
Intensity:
D0 Abnormally Dry
D1 Moderate Drought
D2 Severe Drought
D3 Extreme Drought
D4 Exceptional Drought
The Drought Monitor focuses on broad-scale conditions. Local conditions may vary. See accompanying text summary for forecast statements.
(c) 1 August 2017 USDM
Author:
Deborah Bathke
National Drought Mitigation Center
USDA
NDMC
http://droughtmonitor.unl.edu/
(d) July 2017 Soil Moisture
(e) May-July 2017 Precipitation
Percentile Rank Relative to 1979-2017
Record (0-5)
6-10
11-20
21-30
31-100

Fig. 3.tif



Graphical Abstract.tiff