Flash droughts present a new challenge for subseasonal-to-seasonal prediction

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Flash droughts are a recently recognized type of extreme event distinguished by sudden onset and rapid intensification of drought conditions with severe impacts. They unfold on subseasonal to seasonal (S2S) timescales (weeks to months), presenting a new challenge for the surge of interest in improving S2S prediction. Here, we discuss existing prediction capability for flash droughts and what is needed to establish their predictability. We place them in the context of synoptic to centennial phenomena, consider how they could be incorporated into early warning systems and risk management, and propose two definitions. The growing awareness that flash droughts involve particular processes and severe impacts, and likely a climate change dimension, make them a compelling frontier for research, monitoring, and prediction.

Drought is perhaps the most complex and least understood of all “weather and climate extremes”[1]. Drought can span timescales from a few weeks to decades, and spatial scales from a few kilometers to entire regions. Their impacts usually develop slowly, are often indirect and can linger for long after the end of the drought itself. The drought risk, therefore, is often underestimated and continues to remain a “hidden” hazard[2]. A comprehensive overview of traditional drought characteristics, processes, mechanisms, and impacts is provided in Ref. 3.

In a future warmer climate droughts are likely to increase in duration and intensity in many regions of the world[4,5]. A better understanding of drought phenomena, especially of the physical processes leading to drought, their propagation through the hydrological cycle, the societal and environmental vulnerability to drought and its wide-ranging impacts, is more important than ever. The key challenge is to move from a re-active society responding to impacts to a pro-active society that is resilient and adapted to drought risk, i.e. adopts proactive risk management strategies[3,6].

Droughts whose impacts arise in part from their long duration, such as the Dust Bowl and the 2011-2015 California drought, have formed strong imagery in the US, and megadroughts lasting more than 20 years have also been documented in tree-ring records. Much research has been conducted on aspects of drought that play out over multiple years, but more recently attention has been drawn to the rapid development of some drought events, in the space of a few weeks - flash droughts – a specific definition for which we will provide below. These events, distinguished by their sudden onset and rapid intensification, can have severe impacts[7,8]. Flash droughts develop on the subseasonal-to-seasonal (S2S) timescale (weeks to months), and present a new challenge for prediction efforts on that timescale, which are currently surging in interest[9].

One flash drought that brought attention to the phenomenon occurred in the US Midwest in 2012[8,10] (Figure 1). The areal extent of abnormally dry conditions expanded from 30% of the Continental United States (CONUS) in May 2012 to over 60% by August. This event had significant impacts for agriculture and water-borne transportation in the region. While other rapidly developing droughts had been identified before[11], the widespread impacts of the 2012 event caught the attention of the US public and leadership. Flash drought is not confined to the US[12]. Processes that can produce flash droughts are foci of research in China[13,14]. In southern Queensland, Australia, a flash drought in early 2018 de-vegetated the landscape and drove livestock numbers to their lowest level in a century, a significant impact for agriculture[15].

A drought monitoring and early-warning system is the foundation of effective proactive drought policy because it enables notice of potential and impending drought conditions. It identifies climate and water-resource trends and detects the emergence or probability of occurrence and the likely severity of droughts and their impacts. Reliable information must be communicated in a timely manner to water and land managers, policy makers and the public through appropriate communication channels to trigger actions documented in a drought plan, which is particularly critical for flash droughts. That information, if used effectively, can form the basis for reducing vulnerability and improving mitigation and response capacities of people and systems at risk.

In this perspective, we build on a recent review of flash droughts[8] and discuss the observational and predictive skill of key processes with an eye towards impact assessment and early warning of flash drought. We highlight the current understanding of the physical processes that can drive flash droughts, the existing capabilities to predict them, and what is needed to make progress to establish the predictability and effective early warning of flash droughts on S2S timescales. Following earlier suggestions of possible definitions for flash droughts[8,16], we propose, for consideration by the community, two quantitative definitions for flash drought that can be used for applications related to operations, analysis of observations, model simulations of present and future climate, and assessing S2S initialized-model predictions.

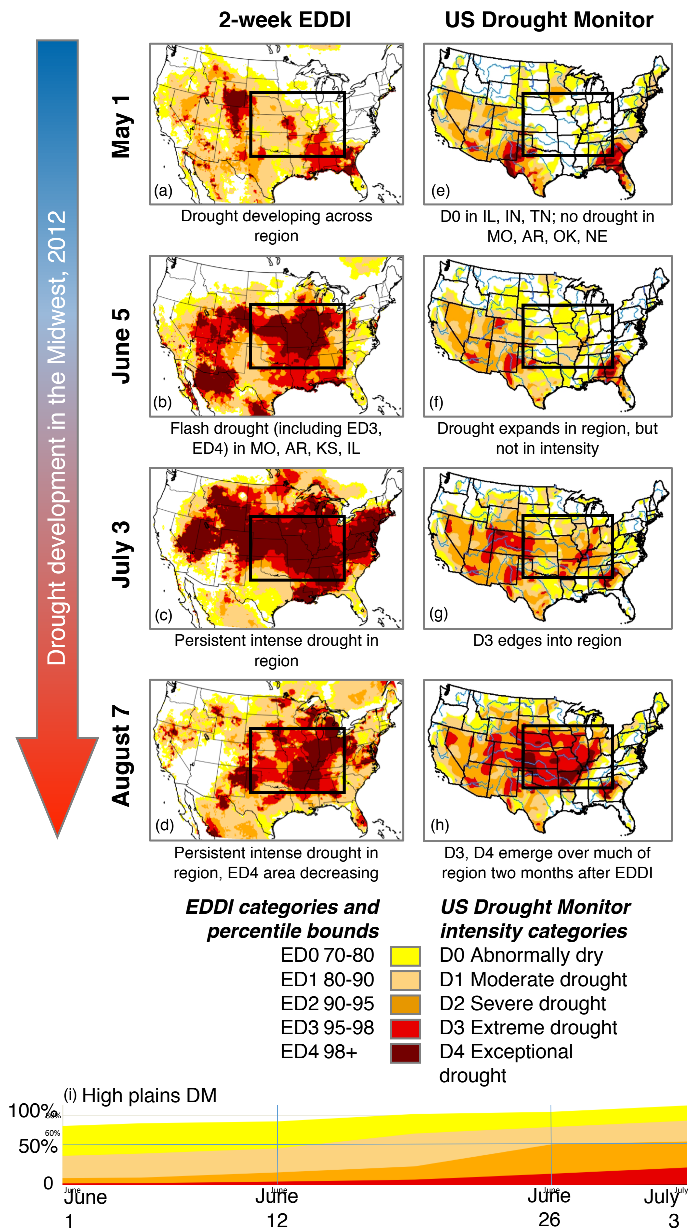

Figure 1. *Evolution of a flash drought across the US Midwest in 2012*. (a-d) Evaporative Drought (ED) categories based on two-week Evaporative Demand Drought Index (EDDI) at five-week intervals during the drought onset. (e-h) US Drought Monitor (USDM). Adapted from Ref. 17. (i) Percent of High Plains region in USDM categories from 1 June- 3 July 2012.

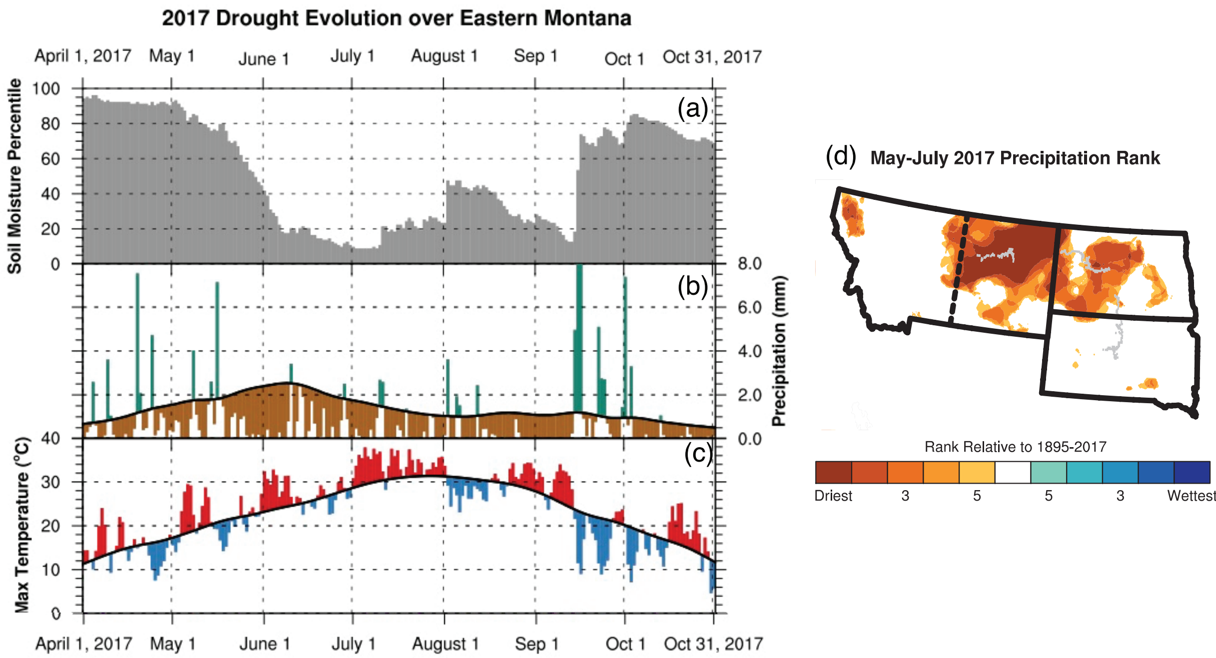

Figure 2. *US Northern Great Plains flash drought in May 2017.* (a) Soil moisture percentile from the top 1 m from University of Washington simulation of the Variable Infiltration Capacity (forced by an estimate of the time-varying meteorology[19,20]; climatological and 2017 (b) precipitation and (c) daily maximum temperature from a collection of GHCN-D stations depicted as departures from the long-term climatology (solid black lines). (d) Rank of accumulated May-July precipitation relative to the 1895-2017 climatology. The timeseries are data averaged over eastern Montana (demarcated by the dotted line in the right panel). Adapted from Ref. 21.

1. Physical processes that produce flash drought

To illustrate the physical processes involved with producing a flash drought, we consider another recent flash drought, in the US Northern Great Plains in 2017. This event shows some recurring flash-drought characteristics, including precipitation deficit and above-average temperatures preceding or coinciding with a rapid soil moisture decline (Fig. 2). Precipitation deficits began before April, when precipitation would climatologically increase. Soil moisture was nonetheless high in April, but continued precipitation deficits throughout the month eroded it slowly at first, before a rapid decline in May.

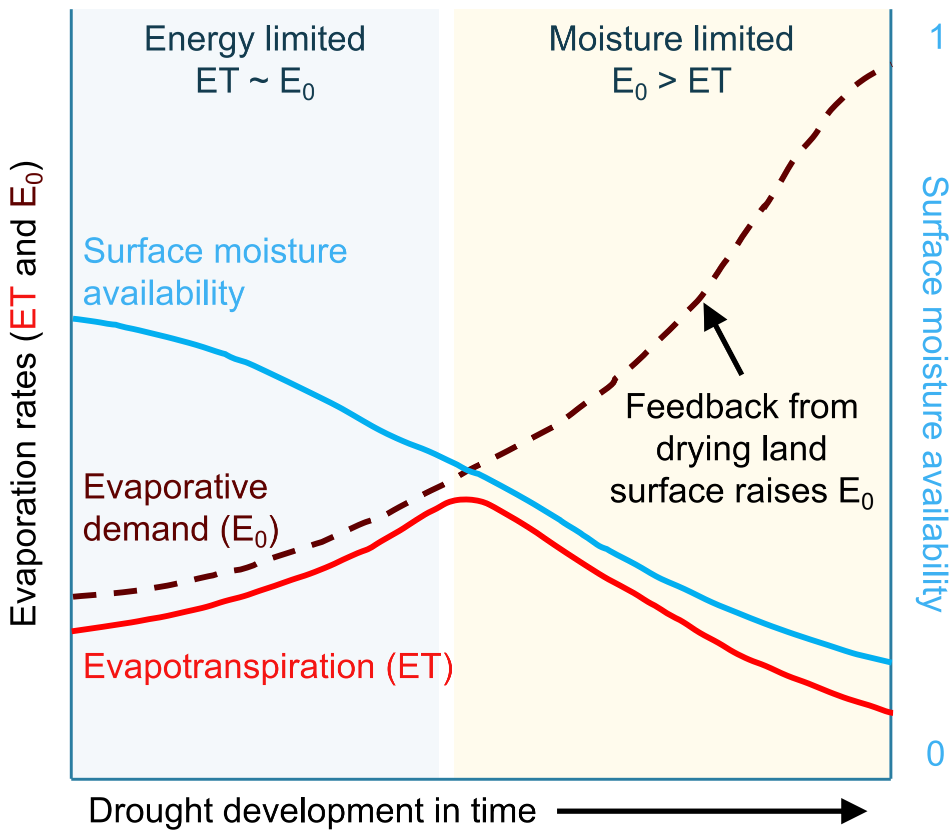

Figure 3. *The response of evaporative demand and evapotranspiration to feedbacks from drying land.* Schematic evolution of evaporative demand (E_0), evapotranspiration (ET), and surface moisture availability, starting from a wet (energy-limited, left side) state and developing into a dry (water-limited, right side) state. Figure adapted from Ref. 22.

We can examine the physical processes driving land surface moisture balance to understand mechanisms that can lead to rapid drought intensification[23,24]. Moisture flux into the surface is driven by precipitation. Like other types of drought, precipitation deficit often plays an important role[25]. Moisture flux away from the surface - evapotranspiration (ET) - can also play an important role in flash drought, driving feedbacks between the land and atmosphere. An important concept is the demand for moisture from the atmosphere - evaporative demand, which is the amount of evaporation that would occur given an unlimited supply of moisture. Evaporative demand can be thought of as the "thirst" of the atmosphere. It both drives and responds to ET. Starting from a state with sufficient soil moisture (energy-limited conditions; Fig. 3), evaporative demand and evaporation vary together - when evaporative demand increases, evaporation follows. With enough evaporation and no replenishment, surface moisture eventually becomes insufficient to supply further water for evaporation; water becomes the limiting factor. Under water-limited conditions, further increases in evaporation can no longer continue, and evaporation decreases. If the same factors that had been driving increases in evaporative demand persist, then evaporative demand will diverge from evaporation. Meanwhile, sensible heat flux increases instead of evaporation, which increases near surface air temperature and vapor pressure deficit, and thus also evaporative demand - an amplifying feedback[26–28].

While much of the focus on flash droughts has been in humid regions, flash droughts and their impacts are also a concern in semi-arid and arid regions where evaporative demand usually exceeds evapotranspiration (locations that start on the right side of Fig. 3; Section 5). Starting from a dry, moisture-limited state, flash droughts in arid regions can be driven by precipitation deficits, and amplification of warm air temperatures by sensible heat flux feedbacks is also of concern.

The local moisture imbalance during flash drought is conditioned by large-scale atmospheric circulation. The large-scale circulation can modify the frequency and intensity of precipitation, and it can increase evaporative demand by reducing cloud cover (which increases incoming solar radiation at the surface), increasing wind speeds and/or increasing temperatures[16,29,30]. In the midlatitudes in summer, this can involve a persistent "blocking" pattern, with a strong quasi-stationary ridge of positive geopotential height anomalies and associated anomalously high surface pressure[16].

Large-scale atmospheric circulation associated with flash droughts can vary from one event to the next and between different regions. While moisture-bearing storms were largely absent during the 2012 US Midwest flash drought, the atmospheric circulation during the event varied from one month to the next[29]. For the southern US Great Plains, the atmospheric circulation associated with rapid declines in soil moisture in conjunction with precipitation deficits can be different from the atmospheric circulation associated with rapid declines in soil moisture in conjunction with heat waves[30].

Flash droughts may be triggered or exacerbated by compound extreme events - extremes of multiple factors that occur simultaneously[31]. A classic example would be an extreme deficit of precipitation coinciding with a heat wave, such as occurred in southern Queensland in January 2018[15]. If these are superimposed on more slowly evolving factors, like a building soil moisture deficit, rapid onset or intensification of drought conditions can result.

Vegetation type can also influence flash drought through its mediating role in transpiration. Trees become moisture-stressed over the course of long-term drought, while in contrast, crops and pasture can be moisture-stressed much more quickly, and might be more sensitive to moisture in the upper soil layer.

2. The challenge of drought for S2S prediction

Compared to slowly-evolving droughts, the relatively fast development timescale of flash droughts requires different approaches to monitoring and prediction. Many drought prediction and monitoring products are updated at monthly or at most weekly timescales. Given a flash drought's onset timescale of only a few weeks, these are not sufficient. Instead, products that update daily are required. This provides an opportunity to leverage synoptic weather forecasts in combination with seasonal forecasting efforts that have recently become available at shorter recently, such as the SubX system[32].

Prediction efforts focused on flash drought are currently in their infancy. One key challenge is skillfully forecasting precipitation deficit on the S2S timescale. However, for a successful flash drought prediction, more is needed than just a forecast of deficient precipitation. Prediction skill is also required of other potential ingredients of rapid drought onset and intensification: high temperatures, low humidity, strong winds, and excess solar insolation. In the 2012 US Midwest event, high temperatures and precipitation deficits may have been driven by a blocking high, while the substantial soil moisture deficit may have been due to anomalous seasonal circulation associated with La Niña[33]. For other flash drought events and locations, other processes and phenomena likely contribute to or affect development, such as land-atmospheric interaction, the Madden-Julian Oscillation (MJO), the Southern and Northern Annular Modes (SAM, NAM), and the Indian Ocean Dipole (IOD). Each of these have been argued to provide or influence predictability of surface-climate variables on timescales relevant for flash drought[34–37] and are fundamental to the prospects of S2S prediction[38].

Global coupled prediction systems show some S2S skill for precipitation[39–41] and temperature[41–44]. Seasonal forecasts of evaporative demand are more skillful than for precipitation over the continental US[45], and at least as skillful globally[46]; though skill for extreme conditions on subseasonal timescales, which may be more relevant for flash drought, has not been established. Predictions are only as accurate as the models that make them. In the case of global climate models, which are the primary tool for S2S prediction systems, there are significant biases. For example, a challenge for US flash drought prediction is a summertime dry and warm bias over the central US in many models[47]. Another key factor for prediction is the fidelity of teleconnections; some models have biased MJO teleconnections[48] that could play a role in flash drought predictions. Furthermore, land surface models underestimate characteristics of evaporative drought[49].

Establishing predictability and credibility of predictions present considerable challenges. One aspect is the number of past flash droughts needed to build up a large enough set of samples to test hindcast efficacy. One property of a flash drought is that it is an unusual event. If the expected return period were more than a year, then testing predictability using hindcasts would require at least 20 years of hindcasts; this is more than is available for some current operational S2S prediction systems[50]. Achieving this will be a continuing challenge with limited computing resources that face competing demands from increased model resolution, ensemble size, and the number and complexity of physical processes.

Other challenges for flash drought prediction lie in our ability to monitor the current state of the land surface and soil, and to use this information to initialize forecast models. The initial state of the soil moisture profile is expected to have greater impact on S2S predictions than on shorter or longer timescales[51]. Despite recent improvement, accurate monitoring of soil moisture is still poor compared to many meteorological variables. Perhaps even further afield from operational systems, but still of potential importance, are interactions between vegetation and the land surface. Dynamic vegetation models (such as ecodemographic models[52]) are becoming available, but initializing them in an operational context will present another challenge.

3. Context within longer-timescale droughts and climate change

The factors driving flash drought can change with climate variability and change on longer timescales, but only a few studies have examined observed regional trends in flash drought (using varied definitions)[53–55] so how they could be affected by different climatic background states remains unclear. In this section we consider the context within which flash droughts occur, and how climate background states, multi-decadal variability, and climate change can influence flash droughts.

Human influence has been identified on various aspects of hydroclimate, including droughts[56,57]; external forcing that drives anthropogenic climate change will significantly change the background climate state as we move further into the 21st century. Future changes to precipitation, temperature and atmospheric circulation will all induce changes to surface water availability and evaporative demand[58] and would thus affect flash drought. Aridity, defined in terms of evaporative demand, increases in many drought-prone regions in climate-change projections[59], and also influences soil moisture[60]. But how evaporative demand is formulated - via temperature-dependent measures like the Palmer Drought Severity Index (PDSI), versus more comprehensive measures - can alter its projected response[61–64]. Actual evaporation and its changes are mediated by vegetation and growing season length, which can counter or exacerbate increasing evaporative demand[65–68]. How these changes in aridity, evaporation, and land-atmosphere feedbacks[69] affect flash drought should be a research priority.

Flash droughts can manifest as discrete drought episodes (e.g., the 2012 US Midwest drought[29,70]), but they may also manifest as a rapid increase in severity from a longer-term drought already in progress. If they are not terminated, they may continue into a period of longer-lasting drought (e.g., the 2018 eastern Australian drought[15]). Flash droughts can be embedded within climate variability occurring at decadal and longer timescales; the characteristics of the more slowly varying climate will influence the impact of a flash drought. Centuries-long records of climate from paleoclimatic data are useful[58] for understanding how short, severe droughts that might have developed rapidly are distributed over longer timescales and under a variety of climate conditions.

While temporal resolution of even the highest-quality paleoclimatic data is insufficient to capture subseasonal timescales, these records can nonetheless provide insights on the frequency and distribution of extreme single year or multi-year drought events. In particular, annually-resolved tree-ring reconstructions of streamflow for the Colorado River document these extreme occurrences over the past 1200 years under varying baseline climates[71]. If a "paleo flash drought" is defined as a year with flow less than two standard deviations below average, then it is possible to identify and characterize periods during which paleo flash droughts occur. For example, in the medieval period (900-1300 CE), characterized by persistent droughts and temperatures warmer than during any period until the last few decades in southwestern North America[72], the mid-12th century period of persistent drought had no occurrences of flash drought years in Colorado River streamflow[71]. The 13th century, which was also dry but less persistently so, contained two flash drought years. However, the most notable cluster of flash drought years occurred between 1495-1506, a 12-year period during which four flash droughts occurred; this was not a period of particularly persistent drought. Similar behavior can be found in streamflow reconstruction of the Upper Rio Grande[73], where only one of three flash drought clusters in a record over 500 years long was associated with persistent drought conditions. Furthermore, paleo reconstructions contain years where runoff efficiency is lower than expected from annual streamflow alone[74,75]. Notwithstanding reconstruction uncertainties, such years could have harbored flash droughts that affected runoff efficiency while leaving little imprint on annual streamflow.

Slowly varying or changing background states present an additional challenge for S2S prediction of flash drought since the climatic base state can alter S2S predictive skill. For example, a decline in the predictive skill of Eastern Pacific El Niños in the early 21st century has been attributed to a change in the background state of the tropical Pacific[76]. Potential changes in S2S skill as the climate baseline evolves need further investigation.

4. Proposed definition

We have seen that the physical processes leading to flash drought are a matter of ongoing research; we will see that specific impacts of flash drought are too. To facilitate the identification of flash droughts, we adopt three principles to describe them that are broadly consistent with previously proposed definitions[8,16] and that lend themselves to analysis yet remain useful for monitoring and prediction. Then, we apply these principles to propose two specific quantitative definitions of flash drought: one for US operations with the US Drought Monitor (https://droughtmonitor.unl.edu/AboutUSDM/WhatIsTheUSDM.aspx), and another that can be used globally for analysis of observations and climate models.

The first principle is that the event should involve a rapid onset and intensification, as emphasized previously[8]. To adequately reflect the rapid onset rate, the onset period should be short enough to distinguish flash droughts from the general population of droughts, encompassing the upper tail of the distribution of events. The second principle is that the intensification rate should be high, as advocated previously[8]. The third principle is that the event should end in a state severe enough to qualify as drought. These principles should apply across drought types, sectors, regions, and seasons, and not only be adapted to definitions based on different variables (precipitation or drought indices) but also offer broad guidelines for the development of specific flash-drought definitions. An additional principle that would be desirable is that the event should have impacts to qualify as a flash drought, but this requires more work to quantitatively document past and potential future impacts.

Next, we propose two quantitative definitions of sub-seasonal flash drought that encompass some of the principles outlined above, using the 2012 US Midwest event as guidance. These definitions follow from recommendations made previously[8] and are designed to be quantitative measures than can be evaluated in the context of past flash droughts, used operationally, and also applied to model simulations analyses and forecast evaluations. Their purpose is not to make further prescriptions, but rather to provide concrete definitions for scrutiny and analysis by the community. The eventual goal is to arrive at quantitative, usable definitions – whether these or a revision.

The first definition is based on Evaporative Demand Drought Index (EDDI, https://www.esrl.noaa.gov/psd/eddi/), which is an experimental drought monitoring and early-warning guidance tool based on how anomalous the evaporative demand is for a given location. The caveat accompanying EDDI is that for a flash drought to develop, the enhanced atmospheric demand should not be compensated by increased precipitation[8]. The second definition, useful only for US operations and based on a previous proposal[8], relies on the US Drought Monitor (USDM) and can be applied in near real-time for early warning applications:

1--Flash drought (applications: international operations, prediction, research): 50% increase in EDDI (toward drying) over two weeks, sustained for at least another two weeks

2--Flash drought (application: US operations): Two-category change in the USDM in two weeks, sustained for at least another two weeks

Regarding the second definition above, the USDM is a weekly operational product based on multiple inputs from observations (e.g., weather, climate, hydrology) and empirical input from regional observers and expert judgement evaluations from the team of scientists (authors) who curate the USDM[7]. A caveat limiting application of this definition to the US is that the USDM involves expert judgement, beyond raw input of observational data, and hence its flash drought definition cannot be directly applied outside of the US operational setting, although drought monitors in other countries could also be used (e.g., https://droughtwatch.eu). Even with that caveat, since the USDM is familiar and widely referenced by stakeholders and other users, basing a flash-drought index on the USDM categories would have a readily applicable operational utility not possible from other indices. Following from conditions experienced in recent events (Fig. 1 and 2), the rapidity of onset of flash drought conditions is reflected by requiring a two-category change in the drought monitor in a two-week period. Impacts can emerge on the timescale of weeks during a flash drought, so this definition requires the two-category change in the drought monitor index to be sustained for at least another two weeks after it is established. This definition includes no prescription beyond this four-week period - the event could persist beyond that time or it could terminate. For example, during the US Midwest 2012 event (Fig. 1), 45% of the High Plains went from D0 (“Abnormally dry”) to D2 (“Severe drought”) between June 12 and June 26, a two category change in the USDM in two weeks.

A more general flash drought definition is the first one listed above, which can be used for international operations, prediction, analysis of observations and climate model output, research into future projections, and applications to periods prior to the USDM. This general definition is based on EDDI, which is multi-scalar and can be calculated at 1-week through 12-month timescales and can capture drying dynamics that operate at the timescales of flash droughts. EDDI provides information on the emergence and persistence of anomalous evaporative demand in a region. The rapid onset characteristic is reflected in the EDDI-based definition by requiring an increase in EDDI of 50 percentiles (toward drying) over two weeks, which must then be sustained for at least the next two weeks. Again returning to the guidance for this definition provided by the US 2012 event (Fig. 1, left), there are large areas of the US that experienced at least a 50% change in the EDDI from June 5 to July 3.

Related to changes in EDDI are changes in soil moisture. The spatial pattern of the frequency of occurrence of 40-, 50-, and 60-percentile decreases in soil moisture during a 20-day period over approximately the last 100 years are shown in Figure 4.

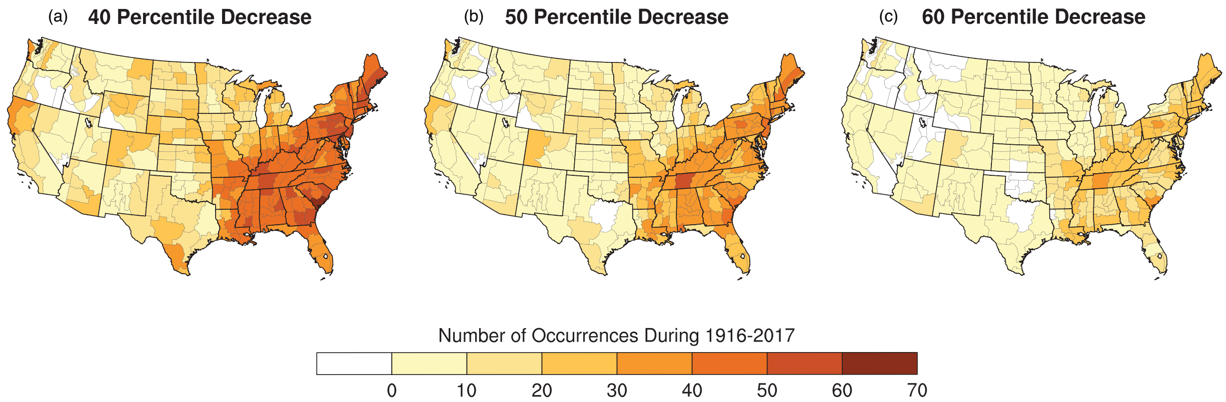

Figure 4. *Frequency of different drought intensification rates.* Frequency of soil moisture decreases exceeding 40th-, 50th-, and 60th-percentile thresholds over four pentads for a 100-year period (1916-2017).

A phenomenon related to but separate from flash drought is *rapid-intensification snow drought*, which occurs when snowpack has a sudden and fast decline. These are of particular concern for regions that rely on snowpack for water supply and power generation. A rapid-intensification snow drought can be induced, for example, by dust-on-snow, rain-on-snow, or anomalously warm temperatures[77]. Other processes that drive a rapid decrease in snowpack could also include advection or sublimation events, for example due to high winds. Because of the cross-timescale interactions between snowpack loss and impacts, and the substantial differences in processes from the flash droughts discussed above, we propose that rapid intensification snow drought should be considered separately from flash drought. Nonetheless, due to its impacts, rapid-intensification snow drought also requires attention[78].

The next steps are to test and apply these definitions retrospectively, to verify that they appropriately encompass events generally described as flash drought events, that they are sufficiently rare that they describe unusual events, and that they describe events that are impactful in one or more dimensions. Extending the definition to require that impacts occur would require quantifying those impacts; this could be addressed by extending the definitions. Further refinement of flash drought definitions may also be useful for specific regions, seasons, sectors, and drought types, using criteria of sufficient intensification rate, impact, and rarity[8]. That said, these definitions are designed as proposals to elicit discussion in the community over their appropriateness and applicability. It is expected that they would be fine-tuned in the future.

5. Impacts-based early warning

Impacts particular to flash drought arise from its rapid and intense development. Because drought response plans developed by communities and governments are often designed around slower-onset events which unfold over the course of months, rapid onset and intensification have the potential to inhibit the initial response – there may be less time than what is allocated to prepare or implement mitigation measures. In the 2012 US Midwest flash drought, during the May-July growing season, dry weather dominated the agricultural areas in the Central Plains and Midwest. Several states had record dry seasons: Arkansas (April-June and other seasons), Kansas (May-July), Nebraska (June-August and other seasons), and South Dakota (July-September). Impacts included, but were not limited to, the reduction in crop yields and commerce-related activities on major river systems. The Mississippi River had water levels that went below 2-m depth, and was closed to navigation three times with less loads carried, barges running aground, slower speeds, and increased dredging costs. The US summer drought of 2012 also contributed to unusually high acreage burned by wildfires. The 2017 Northern Great Plains flash drought also brought wildfire and affected water resources and agriculture[21].

Severity of drought impacts are not only aggravated by other climatic factors, such as high temperatures, high winds, and low relative humidity, but also by the timing (i.e., principal season of occurrence, delays in the start of the rainy season, and occurrence of rains in relation to principal crop-growth stages) and effectiveness of the rains (i.e., rainfall intensity and number of rainfall events)[3]. Other impacts may be associated with hazards that compound drought, such as heatwaves, wildfires, and soil erosion. These may induce public-health effects of heat stress or air quality degradation due to forest fires. Water quality may degrade, affecting aquatic habitats. Depletion of water storage, low river flows and associated consequences for water supply systems and hydropower production can occur with flash drought, though perhaps with some delays. The recreation sector could feel impacts from wildfire as well as low river flows. This impact- and sector-specific vulnerability to flash droughts requires more in-depth investigation, especially as buffers against drought impacts (such as water storage, or grain/feed stores for livestock agriculture) are used up more quickly than for slower-onset drought.

Even though much of the focus of flash drought has been on humid regions where agriculture is a primary activity, impacts are also keenly felt in arid and semi-arid regions. A baseline environment that is already water stressed leaves arid regions more vulnerable to drought with less buffer until impacts are felt. For example, a flash drought could deplete reservoirs, affecting both water availability and hydropower generation capacity in places like the Southwest US, where water is highly managed. Because some physical mechanisms (Section 1) and impacted systems will differ from humid regions, understanding and predicting flash droughts to provide early warning in arid regions presents an additional challenge.

Overall, some types of flash drought-related impacts will present different challenges from slower-onset drought. An accelerated "time to impact" from the onset of a meteorological drought also means that forecasting gains importance compared to monitoring (which remains important, but not sufficient) in operational drought early warning and risk management. Furthermore, translating drought development into mitigation action, and predicting the likelihood of termination versus continuation into long-term drought, are also important. A systematic assessment of where and when (in terms of seasonal timing) vulnerability to flash drought is highest is needed in order to guide efforts on where prediction and early warning would be most useful.

Early warning can enable communities to prepare for impacts. The United Nations office for Disaster Risk Reduction (UNDRR) has established four key areas of people-centered early warning: risk knowledge, monitoring and warning, communication, and response capability. Early warning systems in such contexts are needed not only for event onset, at which a threshold above some socially acceptable or safe level is exceeded, but also for intensification and duration[79]. The phrase "early warning information system" can be used to describe an integrated process of risk assessment, communication, and decision support, of which an early warning is a central output. An early warning information system involves much more than development and dissemination of a forecast; it is the systematic collection and analysis of relevant information about, and coming from, areas of impending risk that (1) informs the development of strategic responses to anticipate crises and crisis evolution, (2) provides capabilities for generating problem-specific risk assessments and scenarios, and (3) effectively communicates options to critical actors for the purposes of decision-making, preparedness, and mitigation[79].

In summary, with improved monitoring and credible S2S timescale predictions, drought early warning could include flash drought. For risk management before, during and after flash drought events, improvements in monitoring and also predicting not just onset of flash drought but termination of events would be beneficial.

6. Ethics of practice in drought research and applications

The ultimate goal of research on flash drought, like many impactful environmental phenomena, is to avoid or decrease the negative effects of drought on individuals and communities. Inequalities influence the ability of communities to cope and adapt to disasters[80]. Across the early warning and response continuum lie three cross-cutting elements: capacity-building, governance, and gender and social inclusion. These elements are best served through a focus on procedural justice and the resulting ethics of participation[81,82]. Effective information-based services engage affected people and multiple perspectives in the development of knowledge, in decision-making, and as recipients of policies[83,84]. Identifying and understanding how flash drought and other climate impacts affect communities and individuals requires integrating local knowledge about impacts. This is knowledge that is inclusive of many different types of individuals in each community, including people who can successfully and meaningfully engage with those affected in the research and monitoring process. People from many different identities are underrepresented in the environmental science workforce; one well-documented example is women. Women in many parts of the world are at greater risk of harm due to climate-related disasters[80], and yet they remain underrepresented among one influential set of climate scientists - IPCC authors[85]. Improving diversity of the scientific workforce and taking an inclusive approach to engaging with stakeholders, while remaining mindful of those that are not included, is essential to ethical research on weather and climate in general and droughts, including flash drought, in particular.

The following objectives are suggested to support the ethical practice of drought research:

- Enhance engagement between users and researchers
- Develop capacity in the segment of the work dedicated to being an interface with stakeholders and users
- Support individual actions to improve scientific culture
- Make institutional efforts to change the culture of science and its reward system
- Collaborate on interdisciplinary work
- Share research outcomes with society, users, stakeholders

7. Future directions in flash drought research and monitoring

Key areas where progress on flash droughts could be made include improved understanding of events in the recent and more distant past and their impacts; establishing predictability and improving prediction of flash drought events; applying these predictions to improve early warning systems for impending events as well as responding to events as they unfold; and understanding how flash drought will respond to climate variability and change. We identify some key challenges and directions for achieving this below.

In order to identify developing flash drought events, monitoring systems must attend to shorter timescales and more frequent updates than are needed to capture slower, longer-term drought events. Products that are only updated monthly (including, for example, the North American Multi-Model Ensemble, NMME[86]) are not very useful for flash-drought monitoring and prediction. Some countries have drought monitoring and Drought Early Warning Systems. In countries with less monitoring and prediction infrastructure, there is also potential to leverage systems that provide global hydrological information, such as the Global Flood Awareness System (GloFAS)[87], World-Wide Hydrological Predictions for the Environment (HYPE)[88], experimental Global Drought Information Systems (GDIS), Global Drought Observatory (GDO), and Integrated Drought Management Programme (IDMP).

There remain open questions about how to define flash drought. One challenge for identifying flash drought events is their wide variation in spatial scale. What areal extent is sufficient to assert that a flash drought is occurring? Assessment of regions and times of year with high sensitivity to or preponderance for flash drought should also be factored into its identification; model representation of land use and its change can play a role as well. A better understanding of flash droughts requires more in-depth research on relevant compound and cascading physical processes that can trigger or increase the likelihood of a flash drought. These include relationships among soil moisture, land-atmosphere interactions, their connections to large-scale meteorological conditions (and precursor conditions), and how these are forced by remote SST patterns and influenced by internal atmospheric variability. Furthermore, research is needed into how these conditions will change as the climate base state changes[58,89], and to incorporate the changing climate into the definition of flash drought so that flash drought definitions remain meaningful in the future.

Prediction systems focus mostly on physical quantities like precipitation, but the motivation and ultimate goal of flash drought monitoring and prediction is to provide as much anticipatory information as possible of impending impacts of flash drought events, and aid response during and after those events. This requires engagement with relevant stakeholders, building capacity, establishing ethical practices of research to document potential impacts of flash drought and when and where these are a concern, and identifying relationships between flash drought indicators and impacts. Such efforts should cross disciplines and engage researchers and decision makers at all stages that bridge the weather-climate continuum.

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Data availability. EDDI is available for the CONUS at ftp://ftp.cdc.noaa.gov/Projects/EDDI/CONUS_archive and for the globe at ftp://ftp.cdc.noaa.gov/Projects/EDDI/global_archive. The bottom panel of Fig. 1 is generated from the USDM (droughtmonitor.unl.edu). The data analyzed in Figs. 2 and 4 are available from ftp://ftp.cdc.noaa.gov/pub/Public/jeischeid/andy/. The data to generate Fig. 4 is available at github.com/apendergrass/flashdroughtperspectivefigure.

Code availability. The bottom panel of Fig. 1 is generated from the USDM (droughtmonitor.unl.edu). Figs. 2 and 4 were generated following the protocol ftp://192.12.137.7/pub/dcp/archive/OBS/livneh2014.1_16deg/. The code to generate Fig. 4 is available at github.com/apendergrass/flashdroughtperspectivefigure.

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