BAMS
Essay

Getting ahead of Flash Drought:

From Early Warning to Early Action

Jason A. Otkin, Molly Woloszyn, Hailan Wang, Mark Svoboda, Marina Skumanich, Roger Pulwarty, Joel Lisonbee, Andrew Hoell, Mike Hobbins, Tonya Haigh, and Amanda E. Cravens

ABSTRACT: Flash droughts, characterized by their unusually rapid intensification, have garnered increasing attention within the weather, climate, agriculture, and ecological communities in recent years due to their large environmental and socioeconomic impacts. Because flash droughts intensify quickly, they require different early warning capabilities and management approaches than are typically used for slower-developing "conventional" droughts. In this essay, we describe an integrated research-and-applications agenda that emphasizes the need to reconceptualize our understanding of flash drought within existing drought early warning systems by focusing on opportunities to improve monitoring and prediction. We illustrate the need for engagement among physical scientists, social scientists, operational monitoring and forecast centers, practitioners, and policy-makers to inform how they view, monitor, predict, plan for, and respond to flash drought. We discuss five related topics that together constitute the pillars of a robust flash drought early warning system, including the development of 1) a physically based identification framework, 2) comprehensive drought monitoring capabilities, and 3) improved prediction over various time scales that together 4) aid impact assessments and 5) guide decision-making and policy. We provide specific recommendations to illustrate how this fivefold approach could be used to enhance decision-making capabilities of practitioners, develop new areas of research, and provide guidance to policy-makers attempting to account for flash drought in drought preparedness and response plans.

KEYWORDS: Land surface; Drought; Climate prediction; Climate variability; Policy

https://doi.org/10.1175/BAMS-D-21-0288.1
Corresponding author: Jason A. Otkin, jasono@ssec.wisc.edu
In final form 15 August 2022

AFFILIATIONS: Otkin—Cooperative Institute for Meteorological Satellite Studies, Space Science and Engineering Center, University of Wisconsin–Madison, Madison, Wisconsin; **Woloszyn and Lisonbee**—Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, and NOAA/National Integrated Drought Information System, Boulder, Colorado; **Wang**—NOAA/Climate Prediction Center, College Park, Maryland; **Svoboda and Haigh**—National Drought Mitigation Center, University of Nebraska–Lincoln, Lincoln, Nebraska; **Skumanich**—NOAA/National Integrated Drought Information System, and University Corporation for Atmospheric Research, Boulder, Colorado; **Pulwarty and Hoell**—NOAA/Physical Sciences Laboratory, Boulder, Colorado; **Hobbins**—Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, and NOAA/Physical Sciences Laboratory, Boulder, Colorado; **Cravens**—Fort Collins Science Center, U.S. Geological Survey, Fort Collins, Colorado

Flash drought has recently become an active and rapidly evolving area of research within climate, agricultural, and ecological scholarship because of the large environmental and socioeconomic impacts it can cause. The term “flash drought” was coined in the early 2000s to draw attention to a subset of droughts that belie the conventional understanding of drought as a creeping phenomenon that takes months or years to develop (Svoboda et al. 2002). For example, the 2012 flash drought across the central United States developed rapidly over only a few weeks but ultimately affected 80% of U.S. agricultural lands, resulting in $36.9 billion in economic losses (Rippey 2015). The 2017 flash drought across the U.S. northern Great Plains and the Canadian Prairies is another example: in the United States, wildfires burned 4.8 million acres and caused agricultural losses in excess of $2.6 billion (Hoell et al. 2020). Record high temperatures and below-normal rainfall again caused flash drought to develop across parts of the northwestern and north-central United States during the spring and summer of 2021. This event led to a wide range of impacts such as lower crop yields, overgrazed pastures, and wildfires that led to poor air quality and ecological damage (Fig. 1).

Numerous high-impact flash droughts have occurred around the world during the past decade (e.g., Christian et al. 2019, 2021; Nguyen et al. 2021; Parker et al. 2021; Wang and Yuan 2021). Together, they have sparked intense interest within both the research and practitioner communities to improve our understanding of their climatological characteristics, physical drivers, and impacts. We define practitioners as those responsible for warning of, preparing for, and/or managing drought impacts—including those in an advisory role such as state climatologists and people directly affected by drought such as agricultural producers and water managers. A clear conceptualization of flash drought is important to both the researcher and practitioner communities; however, there continues to be differing perspectives about what flash drought is and how it differs from other types of drought. It is also recognized that existing drought monitoring and forecasting tools do not provide adequate early warning for flash drought. Taking the United States for an example, though drought early warning systems (DEWS) are in place across much of the country, model forecasts often struggle to capture flash drought’s swift onset (e.g., DeAngelis et al. 2020). Compounding this is that most state and local drought management programs are designed to mitigate the impacts of slower-developing droughts, which means that they may lack flexible mechanisms to respond rapidly to flash drought.

Fig. 1. **Pictures showing the diverse impacts of flash drought during 2021, including (a) spring wheat in central Montana that did not have enough rain to germinate by 9 Aug, (b) heavily grazed pasture in central Montana on 7 Sep, (c) poor winter wheat heading in southeastern Washington on 21 May, and (d) a grassfire in central South Dakota on 2 Aug. All pictures were obtained from the Condition Monitoring Observer Report for Drought (CMOR-Drought) tool maintained by the National Drought Mitigation Center.**

In this essay, we propose a research-and-applications agenda emphasizing the need to reconceptualize our understanding of flash drought, and to focus on specific research opportunities to meet the needs of operational forecasters, policy-makers, and practitioners. We begin by presenting a framework for understanding flash drought and provide specific recommendations in three key research areas: monitoring, prediction, and impact assessment. We then address the policy implications of flash drought and provide thoughts on how to incorporate flash drought research into DEWS. This essay expands upon other recent flash drought reviews (e.g., Otkin et al. 2018a; Pendergrass et al. 2020) and incorporates findings from a first-of-its-kind cross-sectoral workshop convened by the National Integrated Drought Information System (NIDIS) of the National Oceanic and Atmospheric Administration (NOAA) in December 2020 to explore characteristics and definitions of flash drought and to coordinate and co-develop a research agenda to address its diverse management challenges (Woloszyn et al. 2021). The integrated physical and social science approach to understanding flash drought described in this essay will help guide research and operations to better support decision-making and lessen the impacts of flash drought on society and the environment.

Framing flash drought

Development of a general framework to identify flash drought is necessary to enhance our ability to effectively monitor and predict its evolution across different landscapes and to promote deeper understanding of the physical processes and associated impacts. Lisonbee et al. (2021) classifies most flash drought definitions as one of two types: those that explicitly focus on rapid intensification over a multiweek period, and those that implicitly focus on short events lasting less than a week that may or may not lead to serious economic or environmental impacts. Though such philosophical differences often arise when developing a new concept, the simultaneous use of different types of definitions causes confusion because it means that very different features of the Earth system are referred to as "flash drought." To help address this, Otkin et al. (2018a) argued that all definitions for flash drought should account both for their rapid intensification (i.e., the "flash") and the actual occurrence of moisture limitation leading to impacts (i.e., the "drought"). This framework distinguishes flash drought from slower-onset conventional drought, while also ensuring that these events lead to impacts such as reduced soil moisture or poor vegetation health (Svoboda et al. 2002). Numerous authors have used these guiding principles to devise quantitative flash drought definitions using various datasets (Lisonbee et al. 2021).

The framework described above serves as the basis for the American Meteorological Society's Glossary of Meteorology definition of flash drought as "an unusually rapid onset drought event characterized by a multiweek period of accelerated intensification that culminates in impacts to one or more sectors (agricultural, hydrological, etc.)" (American Meteorological Society 2022). Overall, this framework captures the essence of flash drought, though minor revisions may be needed to refine the concept. The most important change would be to recognize that the period of rapid intensification that is the hallmark of flash drought can occur not only at drought onset (as described in the current definition) but also during an ongoing drought. The 2012 flash drought across the United States is a classic example of a rapid-onset event where areas quickly transitioned from a drought-free state to extreme drought over the course of several weeks (Otkin et al. 2016). In contrast, a flash drought across Australia's Murray–Darling basin in 2019 is a representative example of rapid intensification occurring within a background of existing drought conditions (Nguyen et al. 2021). We contend that the term "flash drought" should be applied to both types of events because the period of rapid intensification led to new or worsening drought impacts. If rapid intensification occurs, it should be considered a flash drought regardless of the initial state because rapid onset is essentially a special case of rapid intensification.

As shown by the wide range of definitions used to identify flash drought (Lisonbee et al. 2021), the research community has not yet reached a consensus on quantitative thresholds for important components of the flash drought paradigm. For example, how rapid does the intensification need to be, how long does the period of rapid intensification need to last, and how long must drought conditions persist for an event to be considered a flash drought? Should the definition be designed only to identify flash drought events, or should it also be able to quantify their strength as measured by their rate of intensification and subsequent drought severity? The rate of water depletion from a landscape depends on many factors, such as seasonal precipitation cycles, evaporative demand, soil water holding capacity, and vegetation type. Thus, flash drought definitions should accommodate differences in local characteristics such as how unusual the intensification rate is compared to climatology while requiring that the rapid intensification leads to drought impacts.

Most existing definitions are designed to identify flash drought events by assessing changes in percentiles of a given variable (such as topsoil moisture) over a specified period of time without attempting to quantify the drought severity. This limits their utility because the severity of a flash drought is an important measure of its impact (Otkin et al. 2021). Percentile-based methods are also challenging to use with datasets containing short periods of record because there is insufficient data to fully resolve variations in the tail of the probability distributions that define flash drought. Moreover, it is difficult for such methods to detect flash drought developing from a background that is already in drought. For example, even though a method requiring a minimum decrease of 20th percentiles can identify events that drop from the 40th to 20th percentiles, it will be impossible to capture events starting at the 20th percentile even if conditions rapidly deteriorate from moderate to extreme drought. To alleviate these issues, an alternative approach is to use standardized change anomalies computed from a theoretical continuous distribution because their unbounded range of values is better able to represent the magnitude of extreme events in short datasets (Anderson et al. 2007). Standardized change anomalies also make it possible to compute rapid change indices depicting the cumulative magnitude of moisture stress changes over a certain time period (Otkin et al. 2014). A related issue when using tools originally designed to monitor conventional drought is the potential to misidentify the metric's natural variability as flash drought. Flash drought definitions should control for local variability by assessing how a change in a standardized index fits into the larger population of time changes for that index: if an event belongs to the rapid extreme of this population, then it should be identified as a flash drought; if not, then it represents normal variability for that location, even if it may have otherwise met a percentile-drop criterion.

Regardless of the exact thresholds used in a quantitative flash drought definition, the key point is that it should follow the framework that all flash droughts are characterized by a period of unusually rapid intensification leading to actual drought conditions. This framework is illustrated in Fig. 2 using idealized time series for a generic drought-monitoring variable. Use of this framework to identify rapidly intensifying flash drought will reduce ambiguity in the scientific literature while still allowing researchers to tailor their investigations of flash drought to fit the scope of their research or the needs of regional practitioners. Adherence to this framework will help promote the more efficient study of this important climate phenomenon and the dissemination of drought early warning information to practitioners.

Monitoring

Conventional drought may be described as an extended dry period causing impacts, but flash drought is further constrained within this general population to meet the additional criterion of rapid drying. Because flash droughts reside at the intersection of celerity, dryness, and impacts, they can be classified as "extremes of extremes." Precipitation deficits alone are often insufficient to cause flash drought (Otkin et al. 2013). Rapid drought intensification is more likely when weather extremes such as high temperatures, low humidity, strong winds, and sunny skies combine to enhance evaporative demand (Ford and Labosier 2017). Rapid water depletion from the landscape can occur due to increased evaporation and insufficient replenishment of soil moisture by precipitation. Flash drought is a compound climate event (Zscheischler et al. 2018) characterized by a combination of drivers and hazards that together contribute to societal and environmental risks.

Most studies have identified flash drought based on the presence of unusually rapid changes in evaporative demand, precipitation, soil moisture, evapotranspiration, or vegetation health over several weeks. These quantities are chosen because they capture the main drivers and/or impacts of flash drought on the land surface. Despite the multivariate nature of flash drought, prior studies have typically only used a single drought indicator, such as soil moisture, to examine their climatological characteristics (Lisonbee et al. 2021).

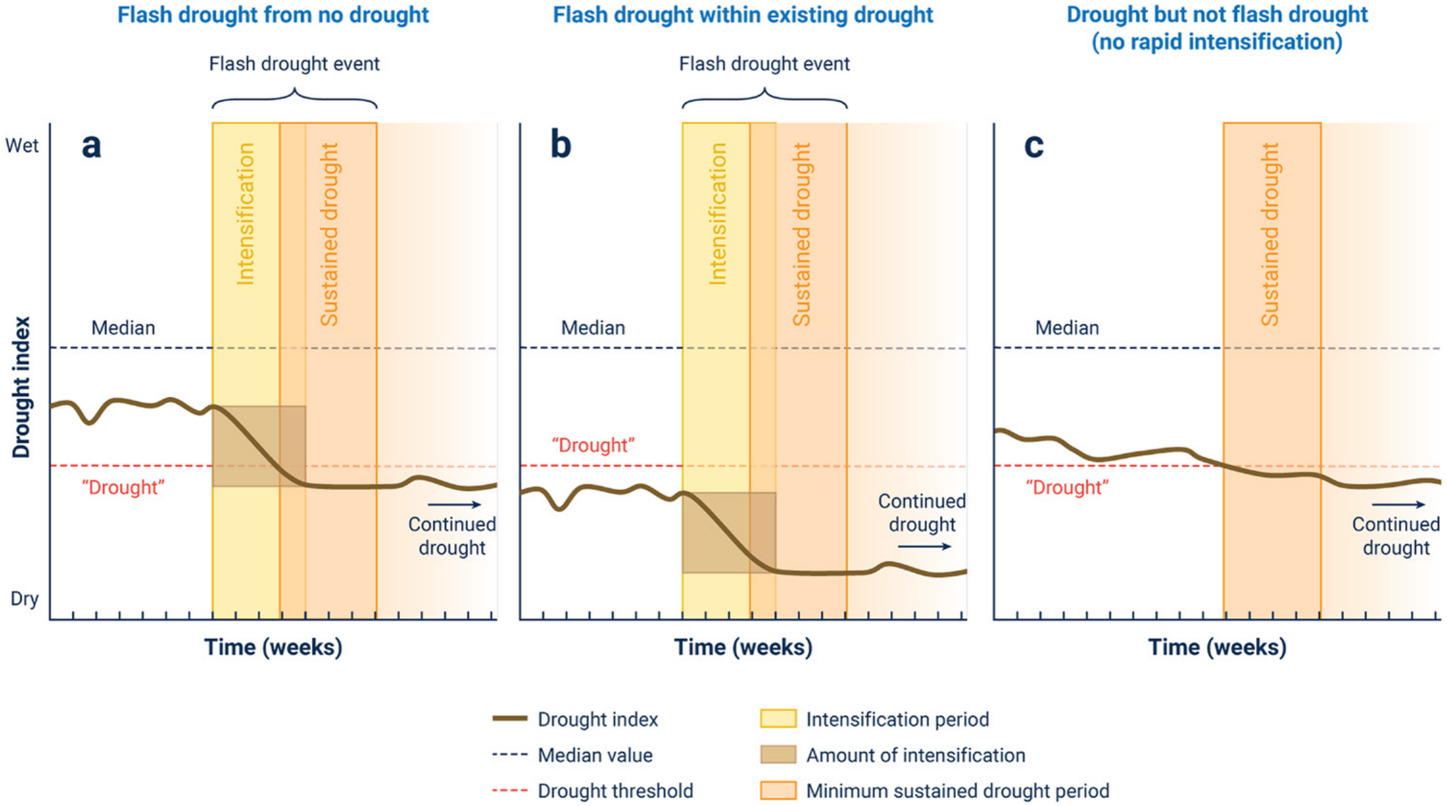


Fig. 2. Idealized time series showing the evolution of a generic drought monitoring index for (a) flash drought development from a drought-free initial state, (b) flash drought development during an ongoing drought, and (c) slow intensification during conventional drought. Time increments along the *x* axis are notional, with agricultural flash drought used in this example to demonstrate the flash drought identification framework. Yellow shading depicts the period of rapid intensification whereas the orange shading denotes the minimum length of time that drought must persist for an event to be considered flash drought. Note that the lengths of the intensification and minimum drought periods shown here are for illustrative purposes and can be adjusted to accommodate the emergence of different impacts or the needs of different practitioners.

In addition, most flash drought definitions are designed to simply identify the occurrence of flash drought, not to assess their severity—this makes it difficult to monitor the evolution of a flash drought and to characterize its changing impacts. We argue that robust flash drought monitoring should account for the multiple meteorological, hydrological, and vegetation anomalies that occur from the onset of a flash drought until its demise. Development and/or enhancement of a monitoring system and tools that comprehensively consider all aspects of flash drought will greatly improve our ability to track their evolution and impacts.

It may be useful to generate a measure of consensus regarding the occurrence and intensity of flash drought using multiple lines of evidence that together encompass both the atmospheric drivers of the hydrological cycle and the impacts of drought at the land surface. Detailed process studies are necessary to quantify how flash drought impacts cascade through the environment and their connection to and interaction with physical and social drivers of drought. If the emerging science uncovers different impacts during flash drought than during conventional drought, then flash drought monitoring tools should be able to capture those dynamics. Existing operational drought monitoring tools may not be sufficiently responsive to flash drought because they were mostly designed to capture slower-developing droughts. Though some modifications could be made to existing tools to make them more responsive to flash drought (such as examining temporal changes in the indices or compositing them over shorter time periods), this illustrates the need to develop multivariate monitoring tools and indices specifically tailored to detect and characterize flash drought. Such tools could be used in both research and operational settings and could serve as a means to improve the prediction of flash drought.

Prediction and predictability

Accurate and reliable prediction of flash drought has been elusive. For example, Earth system models and human-produced predictions provided little to no early warning of the destructive flash droughts that impacted the central United States in 2012 (Hoerling et al. 2014) or the U.S. northern Great Plains and Canadian Prairies in 2017 (Hoell et al. 2020). Steps that could benefit the production of skillful flash drought predictions and their effective communication to practitioners are highlighted in the following paragraphs.

Flash drought physical understanding. Incomplete understanding of the physical drivers of flash drought can hamper their prediction for many reasons. The most obvious is that a process-level evaluation of Earth system models cannot be performed or areas for improvement identified without a sound physical understanding of flash drought and its impacts on the environment. Another reason is that incomplete physical understanding hinders a forecasters' ability to identify and interpret flash drought precursors in the atmosphere, land, and ocean. Adherence to the flash drought framework described above—focusing on rapid intensification leading to impacts—will aid these efforts by providing a solid foundation and a consistent research target for model developers and forecasters, potentially rendering future flash droughts predictable.

Though potential flash drought precursors have been identified for some regions of the world, considerable knowledge gaps remain regarding how local and remote drivers in the Earth system lead to flash drought. Land surface–atmosphere feedbacks have been identified as potential contributors because the interaction of the land surface with the lower troposphere determines the flux of water and energy to and from the land surface (Koster et al. 2010; PaiMazumder and Done 2016). Remotely, atmospheric wave trains—alternating areas of high and low pressure known as Rossby waves—connect weather and climate at a given location to remote phenomena. They can be caused by phenomena that require atmosphere and ocean coupling like El Niño–Southern Oscillation (ENSO; Wang et al. 2017) and Indian Ocean dipole (IOD; Saji et al. 1999), tropical phenomena like the Madden–Julian oscillation (MJO; Jiang et al. 2020), or forcing that may be unrelated to the aforementioned modes of organized climate variability. ENSO has been linked to flash drought in the United States (Chen et al. 2019) and Australia (Nguyen et al. 2020) and the IOD to flash drought events in Australia (Nguyen et al. 2021) and the southeast United States (Schubert et al. 2021). Jong et al. (2022) showed that many flash droughts in the United States are caused by Rossby wave trains arcing across the Pacific Ocean; however, not all of them were forced by tropical modes of climate variability.

Improving flash drought forecasts. New research efforts focused on improving dynamical and statistical models used to produce forecasts would aid the development of accurate and reliable flash drought forecasts. Current subseasonal forecasting systems have limited skill predicting flash drought drivers, particularly precipitation, due in part to model biases in processes such as moist convection, atmospheric teleconnections, and land–atmosphere coupling. Further, land surface models (LSMs)—the essential tool for forecasting impacts of flash drought on the land surface—are subpar in simulating select physical processes (e.g., dynamic vegetation). Enhancements to the atmospheric, land, and oceanic components of subseasonal forecasting systems together with improved initial conditions would improve flash drought forecasts by leading to more accurate forecasts of their drivers and subsequent effects on drought development. Statistical flash drought prediction tools could also be developed by, for example, exploiting machine learning methods. Other measures to improve the accuracy of flash drought forecasts include applying advanced postprocessing to increase the skill and reliability of flash drought indicators, improving land surface forecasts by driving LSMs offline with bias-corrected and calibrated atmospheric forcings, and augmenting dynamical model forecasts by incorporating statistical forecast tools.

Tailored forecast products. Operational flash drought prediction is currently in its infancy, and outlooks that specifically target flash drought and are endorsed by practitioners are lacking. Operational flash drought outlooks should be probabilistic, issued at least weekly, and aligned with sector-specific flash drought impacts (Woloszyn et al. 2021). Ideally, the outlooks would predict not only flash drought onset, but also its severity, persistence, and amelioration. Visualization and dissemination of the outlooks requires collaboration with social scientists and practitioners to ensure effective communication and to integrate their feedback. To make the product user-friendly, flash drought blends that combine forecasts for various flash drought indicators into a single integrated field could be developed. These blends could consider the forecast skill dependence on flash drought indicators, as well as the dependence of flash drought characteristics and impacts by region, season, and economic sector to better address the needs of regional practitioners.

Impact assessments

Flash drought can lead to a wide range of impacts, such as vegetation stress, reduced crop yields, diminished water supplies, ecological degradation, and an enhanced risk for fires. These impacts may differ from those of conventional droughts in magnitude, character, or both. Impacts from flash drought depend on the timing of the rapid intensification, and how long drought conditions persist. Rapid intensification during sensitive times of the growing season may lead to impacts emerging more quickly than can be effectively managed. For example, the 2016 flash drought in the U.S. northern Great Plains led to rapid deterioration of forage resources, which strained the ability of ranchers to maintain their herds (Haigh et al. 2019; Otkin et al. 2018b). Drivers of flash drought such as extreme heat and low precipitation may also increase demand for water from irrigation systems more quickly than managers are able to respond, leading to reduced crop yields and quality (Haigh et al. 2022). Those same drivers may lead to more wildfires, as illustrated by numerous destructive fires during recent flash droughts in the United States (Case and Zavodsky 2018; Hoell et al. 2020). When rapid onset of evaporative stress occurs after robust spring or summer plant growth, large fuel sources can be created as the abundant vegetation rapidly dries out. This can lead to explosive fire development later in the year, as happened in the Marshall Fire in Boulder County, Colorado, in 2021 (Scott 2022).

Much of the focus on flash drought impacts to date has been in the agricultural sector due to the significant economic implications for farmers and ranchers. For example, the flash drought in the U.S. northern Great Plains and Prairie Provinces of Canada in 2017 evolved into the “most destructive drought in decades” in the region (Hoell et al. 2020). Globally, flash drought may be associated not only with economic hardships due to reduced yields but also with widespread food insecurity and even famine due to linked vulnerabilities in rural social systems (UNDRR 2021; Van Ginkel and Biradar 2021). For example, a flash drought that developed during 2010 across Russia and Ukraine significantly affected both the winter and spring wheat crops, leading to a 34% decrease in wheat yield compared to the two previous years (Hunt et al. 2021). Lower global grain stocks due to this flash drought contributed to substantial increases in the prices of wheat and bread that contributed to a cascade of socioeconomic impacts and unrest around the world.

Impacts to sectors other than agriculture have received comparatively little attention. Some practitioners working with water supplies and/or ecosystem health may perceive that flash drought impacts their sectors either minimally or that impacts appear to converge with and become similar in consequence to those that occur during slower-developing droughts. However, neither these relationships nor practitioner's perspectives have been studied extensively. The dearth of research on the ecological and hydrological impacts of flash drought highlights the lack of understanding of potential relationships and feedbacks between flash drought, the environment, and different practitioners, which may vary by region and season. Flash drought impacts ecosystem health through increased wildfires, decreased vegetation productivity, and declining wildlife populations (Hoell et al. 2020). A significant consequence of rapid drought intensification is that it may increase how long a location remains in drought and the likelihood that extreme drought conditions will develop (Otkin et al. 2021). The potential increase in duration and severity due to flash drought is important because emerging ecological research suggests that more severe droughts can push forests beyond their ability to recover (Ploughe et al. 2019; Schnabel et al. 2022).

Another question is how impact assessments for flash drought could or should differ from those for conventional drought. The rapid intensification of flash drought suggests that impacts may become visible or significant more quickly; however, an accurate picture of drought impacts often emerges over long periods of time. Indeed, many drought assessment methods rely on retrospective evaluation (King-Okumu 2019). When considering agricultural impacts, conditions at any one point in the season may not predict the ultimate outcome in terms of yield or quality of crops, which is why many assessments take place at the end of the growing season. The timing and methods of many current impact assessments rarely permit the impact of the flash drought's period of intensification to be disentangled from the impacts of the longer period of drought conditions that may have preceded or followed rapid onset. As understanding grows about when, how, and in what sectors or contexts flash drought has distinct impacts from conventional droughts, it may be necessary to monitor new or different indicators and develop new methods of assessing impacts. The ability to assess impacts relies upon continuous monitoring and collection of drought impacts through existing organization-based impact collection systems and through greater use of alternative sources such as social media (Smith et al. 2021). Finally, researchers and practitioners addressing other rapidly emerging disasters such as hurricanes make frequent use of rapid assessment methods to gather data and quickly characterize consequences; flash drought might require adapting similar techniques to the drought context (Clifford et al. 2022).

Decision-making and policy

The drought research and practitioner communities increasingly recognize that drought is a systemic risk, i.e., one that can cause a breakdown of an entire system rather than simply the failure of individual parts. Therefore, effective drought management requires both proactive approaches to reduce potential impacts of impending events, and where possible, prospective approaches to facilitate adaptive management of new types of risks arising from an evolving climate and other socioeconomic and environmental changes (UNDRR 2021). Proactive and prospective drought risk management includes measures to reduce vulnerability and build both societal and environmental resilience, coupled with recognition of and adaptation to ongoing environmental change (UNDRR 2021; UNGA 2016). This essay reinforces the need to address drought as a systemic risk given the special implications of rapid drought intensification. The occurrence of flash drought with impacts that cascade in nonlinear ways through economies, ecosystems, and livelihoods emphasizes the need to develop integrated approaches to risk management and resilience that include both proactive and prospective policies and actions.

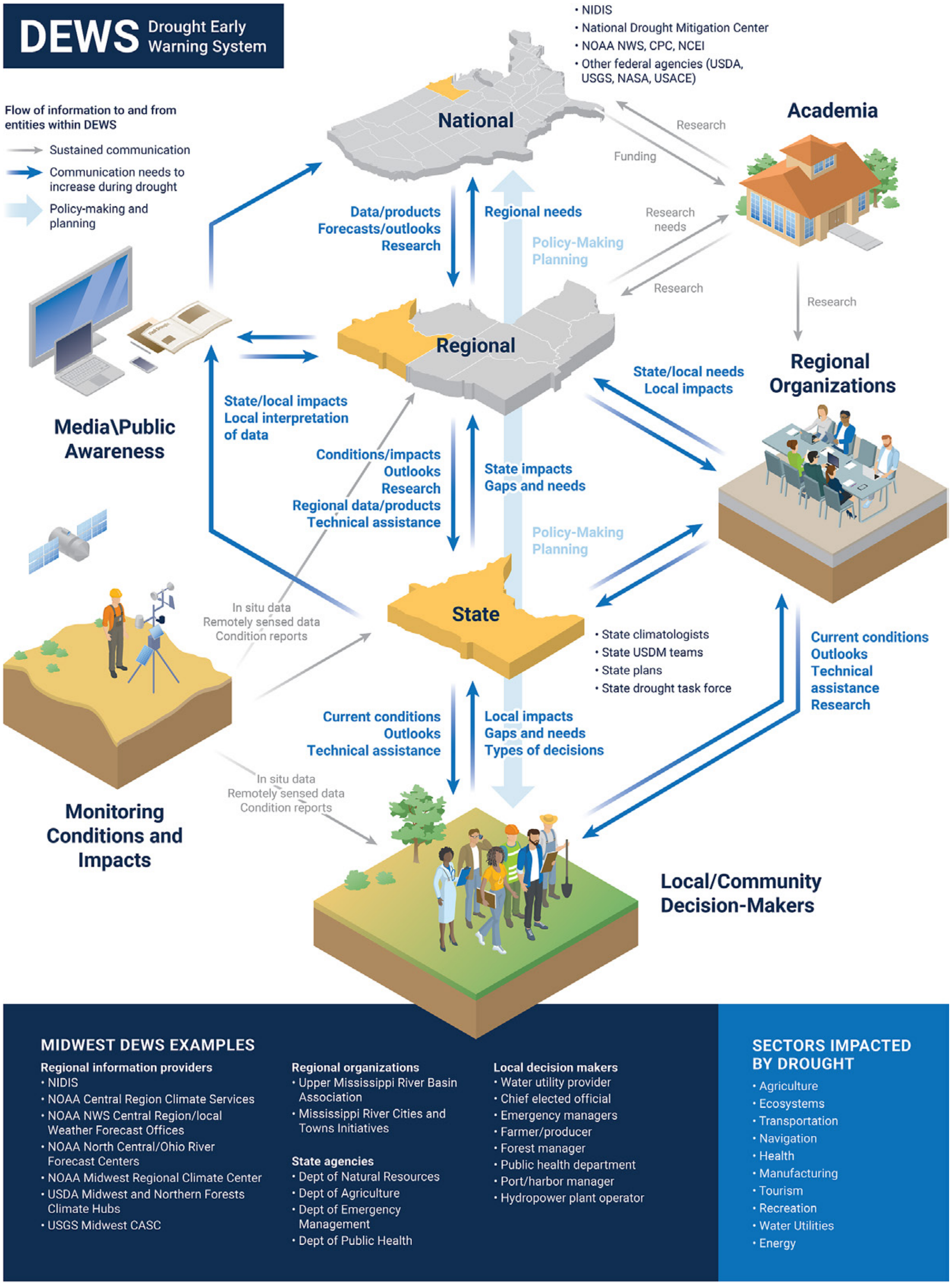
To move to a more proactive approach, the World Meteorological Organization's (WMO) Integrated Drought Management Programme (IDMP) developed a framework to assess and respond to conventional drought risk that consists of the following three pillars (IDMP 2019): (i) monitoring and early warning systems, (ii) vulnerability and impact assessments, and (iii) mitigation, preparedness, and response. Flash drought, which is not explicitly addressed by the current WMO framework, emphasizes the need for early warning systems to be restructured as fully coupled integrated information systems based on understanding both the physical processes underlying drought propagation and impacts and the human role in exacerbating and mitigating drought. An early warning information system is much more than a forecast; it is an integrated risk information and communication system that actively engages communities involved in preparedness and response (Pulwarty and Verdin 2013; Pulwarty and Sivakumar 2014). Effective drought early warning depends upon continuous multisectoral and interdisciplinary collaboration and communication among all concerned actors throughout the process, from monitoring to response and evaluation. This is especially true in the case of flash drought given the shorter window of opportunity to act.

Figure 3 illustrates this continuous collaboration and communication within a DEWS, in this case the NIDIS Midwest DEWS, and the pathways of knowledge and information to and from various entities within the regional network. While national agencies such as NIDIS provide overall coordination and information delivery, regional climate information providers such as the NOAA Central Region Climate Services and the U.S. Department of Agriculture (USDA) Midwest Climate Hubs provide key drought information (e.g., conditions, forecasts, and research) at the local and state level, while local and state partners provide critical on-the-ground condition and impact reports and identify gaps and needs to support effective drought early warning. Other regional organizations, such as the Upper Mississippi River Basin Association and the Mississippi River Cities and Towns Initiative, are key to providing connections to state and local decision-makers.

This figure also emphasizes the subsystems of cooperation and communication that need to increase during a drought event for effective response and decision-making. A key aspect of an effective DEWS is the policy and planning that happens at all levels (e.g., national to local); this response is most effective when informed by knowledge and information from within the system. Flash drought emphasizes the need for DEWS communication channels to be functioning ahead of forecasts of potential events, as the short time scale of rapid intensification requires an even more efficient coordination and flow of information to effectively anticipate and reduce negative impacts. In addition, Fig. 3 illustrates that multiple pathways for interaction are needed, which moves beyond the linear sender–receiver model for information communication.

Timely information relies on continued investments in remotely sensed (e.g., satellite) observations, surface measurements (e.g., stream gauges, soil moisture, and precipitation), and Earth system models, along with the development of interpretive applications and systems to harness the data for decision-making. In the United States, drought information is coordinated and tailored at the national level through NIDIS, working in partnership with the USDA, the U.S. Geological Survey, and other agencies, and at academic research and applications centers such as the National Drought Mitigation Center (NDMC). Access to credible and authoritative information is complemented by the development of technical and institutional capacity to interpret and manage climate-related risks (Pulwarty and Sivakumar 2014). The effectiveness of climate services thus requires sustained and collaborative learning on the parts of data providers and practitioners (WMO 2010; Hoell et al. 2020; Fragaszy et al. 2020).

The need for and benefits of drought preparedness are growing, and especially so in a changing climate (CRS 2021). However, it is also clear from the multidimensional aspects of drought that impact assessments and scenario development can address climate change



Credits: Modeled after the DEWS within the National Integrated Drought Information System (NIDIS). Graphic by Fiona Martin of Visualizing Science.

Fig. 3. Simplified visualization of a DEWS, modeled after the NIDIS Midwest DEWS. The arrows represent the flow of information to and from the entities within the region, with the thicker blue arrows representing the flow of information that needs to increase during flash drought. The thick light blue arrow represents the policy and planning that happens at all levels within the DEWS. The type of information that is exchanged by the various pathways is shown by the text adjacent to the arrows. Specific examples of entities in the Midwest DEWS are shown in the blue box, as well as the sectors impacted by drought in this region.

projections more critically by being tested for reliability and credibility at local levels. Local communities need support in the form of enhanced monitoring and the assimilation of ramped-up surveillance data as events unfold. In addition, because interdependencies exist among agriculture, water, energy, ecosystems, and trade in a region, a more systemic view of drought impacts is essential. This is especially true for flash drought given that rapid transitions often cascade through different systems (e.g., from land surface to air quality concerns). Historically, national policy around drought response and preparedness in the United States has been primarily shaped by state and local actions, federal drought assistance, and dam operations, among other factors (CRS 2021), with most federal financial aid for drought focusing on agricultural production loss and rural water supplies. Therefore, national drought policy would benefit by advancing beyond its current state to more fully incorporate the diverse impacts of drought and to implement mechanisms to respond quickly in the case of flash drought.

This essay makes the case that a modernized view of drought should incorporate flash drought and its cascading impacts. The transition of national, regional, and local drought-risk management efforts to this modernized view of drought would benefit from, among other actions:

- integrating flash drought concerns into policy at multiple levels;
- improving alignment and coordination between entities that provide different types of drought early warning information;
- developing risk and vulnerability profiles of drought-prone regions that include flash drought, along with uncertainties, potential impacts, and benefits of early action;
- mapping available resources (e.g., infrastructure, personnel, communication channels, and supported services);
- implementing systematic and comprehensive collection, monitoring, and assessment of drought impacts—including flash drought impacts—across all sectors; and
- improving awareness of the multidimensional impacts of flash drought and the added economic, social, and environmental value of enhanced early warning information for flash drought at subseasonal to longer time scales.

There is an ongoing need to institutionalize “capacity” and “coordination” at national, regional, and local levels more directly. This need exposes itself vividly when collaborative networks and early warning systems do not exist prior to drought, or attempts are made to create them in an ad hoc manner during times of rapid intensification. The efforts of national, state, and local organizations are helping to overcome this gap, but more needs to be done. Advancing a systems perspective of drought-related risks through proactive and prospective approaches and incorporating both slowly evolving events and rapid-intensification events can help to short-circuit what has been aptly referred to as the “hydro-illogical cycle” (Wilhite 2011). The improved characterization and understanding of flash drought that we propose requires a revision of the assumption that drought is solely a slow-onset phenomenon, and further offers the opportunity to act before critical thresholds have been exceeded. It also offers social accountability through increased public information and transparency in risk assessment and management.

Concluding remarks and next steps

Flash drought has captured the attention of researchers, practitioners, and the general public due to the suddenness with which it appears as well as its major and diverse impacts on agriculture, natural ecosystems, and society. Though recent years have seen tremendous advances in our understanding of this extreme climate phenomenon, substantial work remains to fill scientific gaps and to address the drought early warning and mitigation needs of practitioners and policy-makers. For example, process-based studies are required to improve the monitoring and prediction of flash drought using a multivariate framework that captures their drivers and impacts as they cascade through the environment. Flash droughts influence the land surface in myriad ways, so it is important to use multiple variables to assess their severity and to track their evolution in space and time. To improve subseasonal-to-seasonal forecasts, substantial research will be necessary to enhance our ability to assimilate in situ and remotely sensed observations of the land surface and to more accurately represent biophysical processes controlling how vegetation responds to changes in moisture stress and atmospheric conditions. Improved flash drought prediction will require additional research to explore new sources of predictability, to improve coupled Earth system models, and to develop statistical models. Extensive engagement with practitioners is also necessary to better understand their needs and requirements and to then co-develop tools that will allow them to better prepare for flash drought and to mitigate its impact. Drought early warning information systems that inform response, planning, and policy are critical. Flash drought emphasizes the need for these systems because their rapid intensification requires efficient coordination to effectively anticipate, plan for, and reduce negative impacts. Underpinning all of this work is the need to employ a consistent flash drought identification framework so that researchers, policy-makers, and the general public all refer to the same type of event as flash drought. Use of the generalized identification framework presented in this essay will help reduce confusion and aid coordination of efforts within the research and practitioner communities.

Acknowledgments. We thank everyone who attended the NIDIS Flash Drought Workshop in December 2020 for their comments and perspectives on flash drought. We also thank Joyce Glynn, Scott Wersland, and Perry Beale for submitting three of the drought impact pictures included in Fig. 1 via the CMOR-Drought tool (https://droughtimpacts.unl.edu/Tools/ConditionMonitoringObservations.aspx) maintained by the NDMC in partnership with NIDIS, and Fiona Martin from Visualizing Science for her design support for Figs. 2 and 3. J. Otkin was partially funded by the National Science Foundation PREEVENTS program via Grant 1854931-ICER.

Data availability statement. No datasets were generated or analyzed during this essay.

References

American Meteorological Society, 2022: Flash drought. Glossary of Meteorology, https://glossary.ametsoc.org/wiki/Flash_drought.

Anderson, M. C., J. R. Norman, J. R. Mecikalski, J. A. Otkin, and W. P. Kustas, 2007: A climatological study of evapotranspiration and moisture stress across the continental United States based on thermal remote sensing: 1. Model formulation. *J. Geophys. Res.*, **112**, D10117, https://doi.org/10.1029/2006JD007506.

Case, J. L., and B. T. Zavodsky, 2018: Evolution of 2016 drought in the southeastern United States from a land surface modeling perspective. *Results Phys.*, **8**, 654–656, https://doi.org/10.1016/j.rinp.2017.12.029.

Chen, L. G., J. Gottschalck, A. Hartman, D. Miskus, R. Tinker, and A. Artusa, 2019: Flash drought characteristics based on U.S. Drought Monitor. *Atmosphere*, **10**, 498, https://doi.org/10.3390/atmos10090498.

Christian, J. I., J. B. Basara, J. A. Otkin, E. D. Hunt, R. A. Wakefield, P. X. Flanagan, and X. Xiao, 2019: A methodology for flash drought identification in gridded datasets: Application of flash drought frequency across the United States. *J. Hydrometeor.*, **20**, 833–846, https://doi.org/10.1175/JHM-D-18-0198.1.

——, ——, E. D. Hunt, J. A. Otkin, J. C. Furtado, V. Mishra, X. Xiao, and R. M. Randall, 2021: Global distribution, trends, and drivers of flash drought occurrence. *Nat. Commun.*, **12**, 6330, https://doi.org/10.1038/s41467-021-26692-z.

Clifford, K. R., J. B. Goolsby, A. E. Cravens, and A. E. Cooper, 2022: Rapidly assessing social characteristics of drought preparedness and decision making: A guide for practitioners. U.S. Geological Survey Scientific Investigations Rep., in press.

CRS, 2021: Drought in the United States: Science, policy, and selected federal authorities. Congressional Research Service Rep. R46911, 43 pp.

DeAngelis, A. M., H. Wang, R. D. Koster, S. D. Schubert, Y. Chang, and J. Marshark, 2020: Prediction skill of the 2012 U.S. Great Plains flash drought in Subseasonal Experiment (SubX) models. *J. Climate*, **33**, 6229–6253, https://doi.org/10.1175/JCLI-D-19-0863.1.

Ford, T. W., and C. F. Labosier, 2017: Meteorological conditions associated with the onset of flash drought in the eastern United States. *Agric. For. Meteor.*, **247**, 414–423, https://doi.org/10.1016/j.agrformet.2017.08.031.

Fragaszy, S. R., and Coauthors, 2020: Drought monitoring in the Middle East and North Africa (MENA) region: Participatory engagement to inform early warning systems. *Bull. Amer. Meteor. Soc.*, **101**, E1148–E1173, https://doi.org/10.1175/BAMS-D-18-0084.1.

Haigh, T. R., J. A. Otkin, A. Mucia, M. Hayes, and M. E. Burbach, 2019: Drought early warning and the timing of range manager's drought response. *Adv. Meteor.*, **2019**, 1–14, https://doi.org/10.1155/2019/9461513.

——, ——, M. Woloszyn, D. Todey, and C. Felkley, 2022: Meeting the drought information needs of Midwest perennial specialty crop producers. *J. Appl. Meteor. Climatol.*, **61**, 839–855, https://doi.org/10.1175/JAMC-D-21-0105.1.

Hoell, A., and Coauthors, 2020: Lessons learned from the 2017 flash drought across the U.S. northern Great Plains and Canadian Prairies. *Bull. Amer. Meteor. Soc.*, **101**, E2171–E2185, https://doi.org/10.1175/BAMS-D-19-0272.1.

Hoerling, M., and Coauthors, 2014: Causes and predictability of the 2012 Great Plains drought. *Bull. Amer. Meteor. Soc.*, **95**, 269–282, https://doi.org/10.1175/BAMS-D-13-00055.1.

Hunt, E., and Coauthors, 2021: Agricultural and food security impacts from the 2010 Russia flash drought. *Wea. Climate Extremes*, **34**, 100383, https://doi.org/10.1016/j.wace.2021.100383.

IDMP, 2019: Integrated Drought Management Programme. Accessed 20 August 2019, www.droughtmanagement.info.

Jiang, X., and Coauthors, 2020: Fifty years of research on the Madden–Julian Oscillation: Recent progress, challenges, and perspectives. *J. Geophys. Res. Atmos.*, **125**, e2019JD030911, https://doi.org/10.1029/2019JD030911.

Jong, B., M. Newman, and A. Hoell, 2022: Subseasonal meteorological drought development over the central United States during spring. *J. Climate*, **35**, 2525–2547, https://doi.org/10.1175/JCLI-D-21-0435.1.

King-Okumu, C., 2019: Drought impact and vulnerability assessment: A rapid review of practices and policy recommendations. United Nations Convention to Combat Desertification, 65 pp., www.unccd.int/publications/drought-impact-and-vulnerability-assessment-rapid-review-practices-and-policy.

Koster, R. D., and Coauthors, 2010: Contribution of land surface initialization to subseasonal forecast skill: First results from a multi-model experiment. *Geophys. Res. Lett.*, **37**, L02402, https://doi.org/10.1029/2009GL041677.

Lisonbee, J., M. Woloszyn, and M. Skumanich, 2021: Making sense of flash drought: Definitions, indicators, and where we go from here. *J. Appl. Serv. Climatol.*, **2021** (1), 1–19, https://doi.org/10.46275/JOASC.2021.02.001.

Nguyen, H., J. A. Otkin, M. C. Wheeler, P. Hope, B. Trewin, and C. Pudmenzky, 2020: Climatology and variability of the evaporative stress index and its suitability as a tool to monitor Australian drought. *J. Hydrometeor.*, **21**, 2309–2324, https://doi.org/10.1175/JHM-D-20-0042.1.

——, M. C. Wheeler, H. H. Hendon, E.-P. Lim, and J. A. Otkin, 2021: The 2019 flash droughts in subtropical eastern Australia and their association with large-scale climate drivers. *Wea. Climate Extremes*, **32**, 100321, https://doi.org/10.1016/j.wace.2021.100321.

Otkin, J. A., M. C. Anderson, C. Hain, I. Mladenova, J. Basara, and M. Svoboda, 2013: Examining rapid onset drought development using the thermal infrared based Evaporative Stress Index. *J. Hydrometeor.*, **14**, 1057–1074, https://doi.org/10.1175/JHM-D-12-0144.1.

——, ——, ——, and M. Svoboda, 2014: Examining the relationship between drought development and rapid changes in the Evaporative Stress Index. *J. Hydrometeor.*, **15**, 938–956, https://doi.org/10.1175/JHM-D-13-0110.1.

——, and Coauthors, 2016: Assessing the evolution of soil moisture and vegetation conditions during the 2012 United States flash drought. *Agric. For. Meteor.*, **218–219**, 230–242, https://doi.org/10.1016/j.agrformet.2015.12.065.

——, M. Svoboda, E. D. Hunt, T. W. Ford, M. C. Anderson, C. Hain, and J. B. Basara, 2018a: Flash droughts: A review and assessment of the challenges imposed by rapid-onset droughts in the United States. *Bull. Amer. Meteor. Soc.*, **99**, 911–919, https://doi.org/10.1175/BAMS-D-17-0149.1.

——, T. Haigh, A. Mucia, M. C. Anderson, and C. R. Hain, 2018b: Comparison of agricultural stakeholder survey results and drought monitoring datasets during the 2016 U.S. Northern Plains flash drought. *Wea. Climate Soc.*, **10**, 867–883, https://doi.org/10.1175/WCAS-D-18-0051.1.

——, and Coauthors, 2021: Development of a flash drought intensity index. *Atmosphere*, **12**, 741, https://doi.org/10.3390/atmos12060741.

PaiMazumder, D., and J. M. Done, 2016: Potential predictability sources of the 2012 U.S. drought in observations and a regional model ensemble. *J. Geophys. Res. Atmos.*, **121**, 12 581–12 592, https://doi.org/10.1002/2016JD025322.

Parker, T., A. Gallant, M. Hobbins, and D. Hoffmann, 2021: Flash drought in Australia and its relationship to evaporative demand. *Environ. Res. Lett.*, **16**, 064033, https://doi.org/10.1088/1748-9326/abfe2c.

Pendergrass, A. G., and Coauthors, 2020: Flash droughts present a new challenge for subseasonal-to-seasonal prediction. *Nat. Climate Change*, **10**, 191–199, https://doi.org/10.1038/s41558-020-0709-0.

Ploughe, L. W., E. M. Jacobs, G. S. Frank, S. M. Greenler, M. D. Smith, and J. S. Dukes, 2019: Community Response to Extreme Drought (CRED): A framework for drought-induced shifts in plant–plant interactions. *New Phytol.*, **222**, 52–69, https://doi.org/10.1111/nph.15595.

Pulwarty, R., and J. Verdin, 2013: Crafting early warning information systems-the case of drought. *Measuring Vulnerability to Natural Hazards: Disaster Resilient Societies*, J. Birkmann, Ed., UNU Press, 124–147.

——, and M. Sivakumar, 2014: Information systems in a changing climate: Early warnings and drought risk management. *Wea. Climate Extremes*, **3**, 14–21, https://doi.org/10.1016/j.wace.2014.03.005.

Rippey, B. R., 2015: The U.S. drought of 2012. *Wea. Climate Extremes*, **10**, 57–64, https://doi.org/10.1016/j.wace.2015.10.004.

Saji, N. H., B. N. Goswami, P. N. Vinayachandran, and T. Yamagata, 1999: A dipole mode in the tropical Indian Ocean. *Nature*, **401**, 360–363, https://doi.org/10.1038/43854.

Schnabel, F., and Coauthors, 2022: Cumulative growth and stress responses to the 2018–2019 drought in a European floodplain forest. *Global Change Biol.*, **28**, 1870–1883, https://doi.org/10.1101/2021.03.05.434090.

Schubert, S. D., Y. Chang, A. M. DeAngelis, H. Wang, and R. D. Koster, 2021: On the development and demise of the fall 2019 southeast U.S. flash drought: Links to an extreme positive IOD. *J. Climate*, **34**, 1701–1723, https://doi.org/10.1175/JCLI-D-20-0428.1.

Scott, M., 2022: Wet, then dry extremes contributed to devastating Marshall Fire in Colorado. Climate.gov, 7 January, www.climate.gov/news-features/event-tracker/wet-then-dry-extremes-contributed-devastating-marshall-fire-colorado.

Smith, K. H., M. E. Burbach, M. J. Hayes, P. E. Guinan, A. J. Tyre, B. Fuchs, T. Haigh, and M. D. Svoboda, 2021: Whose ground truth is it? Harvesting lessons from Missouri's 2018 bumper crop of drought observations. *Wea. Climate Soc.*, **13**, 227–244, https://doi.org/10.1175/WCAS-D-19-0140.1.

Svoboda, M., and Coauthors, 2002: The Drought Monitor. *Bull. Amer. Meteor. Soc.*, **83**, 1181–1190, https://doi.org/10.1175/1520-0477-83.8.1181.

UNGA, 2016: Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction. Doc. A/71/644, United Nations General Assembly, 41 pp., www.preventionweb.net/files/50683_oiewgreportenglish.pdf.

UNDRR, 2021: GAR Special Report on Drought 2021. UN Office for Disaster Risk Reduction, 210 pp., www.undrr.org/publication/gar-special-report-drought-2021.

Van Ginkel, M., and C. Biradar, 2021: Drought early warning in agri-food systems. *Climate*, **9**, 134, https://doi.org/10.3390/cli9090134.

Wang, C., C. Deser, J.-Y. Yu, P. DiNezio, and A. Clement, 2017: El Niño and Southern Oscillation (ENSO): A review. *Coral Reefs of the Eastern Tropical Pacific: Persistence and Loss in a Dynamic Environment*, P. W. Glynn, D. P. Manzello, and I. C. Enochs, Eds., Springer, 85–106.

Wang, Y., and X. Yuan, 2021: Anthropogenic speeding up of south China flash droughts as exemplified by the 2019 summer-autumn transition season. *Geophys. Res. Lett.*, **48**, e2020GL091901, https://doi.org/10.1029/2020GL091901.

Wilhite, D., 2011: Breaking the hydro-illogical cycle: Progress or status quo for drought management in the United States. *Eur. Water*, **34**, 5–18, www.ewra.net/ew/pdf/EW_2011_34_01.pdf.

WMO, 2010: Guide to Agricultural Meteorological Practices. WMO-134, 799 pp., https://library.wmo.int/doc_num.php?explnum_id=3996.

Woloszyn, M., and Coauthors, 2021: Flash drought: Current understanding and future priorities. Rep. of the 2020 NIDIS Flash Drought Virtual Workshop, NOAA National Integrated Drought Information System, 53 pp., www.drought.gov/documents/flash-drought-current-understanding-future-priorities.

Zscheischler, J., and Coauthors, 2018: Future climate risk from compound events. *Nat. Climate Change*, **8**, 469–477, https://doi.org/10.1038/s41558-018-0156-3.