FLASH DROUGHTS: A REVIEW AND ASSESSMENT OF THE CHALLENGES IMPOSED BY RAPID ONSET DROUGHTS IN THE UNITED STATES

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Submitted to the *Bulletin of the American Meteorological Society* on 15 July 2017.

Revised version submitted on 29 September 2017.

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Abstract

Given the increasing use of the term “flash drought” by the media and scientific community, it is prudent to develop a consistent definition that can be used to identify these events and to understand their salient characteristics. It is generally accepted that flash droughts occur more often during the summer due to increased evaporative demand; however, two distinct approaches have been used to identify them. The first approach focuses on their rate of intensification, whereas the second approach implicitly focuses on their duration. These conflicting notions for what constitutes a flash drought (e.g., unusually fast intensification versus short duration) introduce ambiguity that affects our ability to detect their onset, monitor their development, and understand the mechanisms that control their evolution. Here, we propose that the definition for flash drought should explicitly focus on its rate of intensification rather than its duration, with droughts that develop rapidly identified as flash droughts. There are two primary reasons for favoring the intensification approach over the duration approach. First, longevity and impact are basic characteristics of a drought’s magnitude. Thus, short-term events lasting only a few days and having minimal impacts are inconsistent with the general understanding of drought and therefore should not be considered flash droughts. Second, by focusing on the rate of intensification, the proposed flash drought definition highlights the unique challenges faced by vulnerable stakeholders who have less time to prepare for its adverse effects when drought develops so quickly.

Drought is a naturally recurring feature of the climate system that affects virtually all regions of the world. Extreme drought events such as those that have occurred across various parts of the U.S. during the past decade have caused major societal disruptions, extensive damage to natural ecosystems, drawdown of surface and groundwater supplies, and sharp reductions in agricultural production. Because droughts occur across multiple time scales (weeks to decades) and exert diverse impacts on different socioeconomic sectors, landscapes, and components of the hydrological cycle, it is difficult to create a uniform definition for drought that applies to all situations. Drought has traditionally been categorized as one of four types: meteorological, agricultural, hydrological, and socioeconomic (Wilhite and Glantz 1985). Meteorological drought refers to a deficit in precipitation over some period of time, while taking into account differences in local climatology. If deficits in net water supply at the surface become large, hydrological drought can develop as reflected by groundwater, river, or reservoir levels dropping below normal. When plant water requirements are not met during the growing season, especially during certain periods critical for yield development, agricultural drought can result. Socioeconomic drought considers the impact of drought conditions on the supply and demand of economic goods and services. More recently, a fifth drought type referred to as ecological drought has been proposed (Crausbay, et al. 2017). This type of drought refers to an episodic deficit in water availability that drives ecosystems beyond thresholds of vulnerability, affects ecosystem services, and triggers feedback between natural and human systems. It should be noted that more than one drought type can occur at the same time at a given location and that droughts can transition from one type to another as conditions and impacts evolve with time.

In addition to these drought types, a potentially new drought type known as "flash drought" has entered the scientific and popular lexicons in recent years. Though a deficit in precipitation is a basic requirement for drought to develop, the speed with which it develops and its ultimate severity are also influenced by other environmental anomalies. For example, if below normal precipitation is accompanied by above normal evaporative demand due to high temperatures, low humidity, strong winds, and sunny skies, agricultural and ecological drought conditions signified by increasing soil moisture deficits and declining vegetation health can rapidly emerge. This scenario has occurred in dramatic fashion several times across the U.S. in recent years. In 2012, large precipitation deficits combined with record high temperatures and abundant sunshine led to very rapid drought development across the central U.S. According to the U.S. Drought Monitor (USDM; Svoboda et al. 2002), widespread areas experienced a 3, 4, or even a 5 category increase in drought severity over a 2-month period, which is a remarkable rate of intensification (Fig. 1a). This means that locations that generally had near normal conditions at the end of May had fallen into extreme drought conditions only two months later. This flash drought had a substantial impact on prime agricultural lands, with losses estimated to be in excess of $30 billion across the entire nation (NCEI 2017). Likewise, in 2016, extreme drought conditions rapidly developed during the fall across a large portion of the southeastern U.S., with an extensive area experiencing up to a 4 category increase in drought severity over a 3-month period (Fig. 1b). Similar to the 2012 event, this drought had a detrimental impact on agriculture and also led to an elevated fire risk, most notably represented by the devastating wildfires that occurred near Gatlinburg, TN in late November. The most recent example of rapid drought intensification in the U.S. occurred across the northern High

Plains in 2017, where warm and exceptionally dry weather during the spring and early summer led to up to a 4 category increase in drought severity over a 2-month period (Fig. 1c) and sharply lower wheat yields across the region. These events demonstrate the suddenness with which extreme drought conditions can develop and the high impact that they have on the economy and local ecosystems. In this paper, we provide an overview of recent research on flash droughts and then present a proposed definition for flash drought and a checklist that can be used to track its development. We also discuss the importance of drought monitoring tools and forecasting methods that can quickly capture flash drought onset and predict its evolution over sub-seasonal time scales.

Flash drought literature review

Drought is often thought of as a slowly evolving climate phenomenon that takes many months or even years to reach its full intensity. However, recent events across the U.S. and elsewhere around the world have shown that droughts can develop very rapidly if extreme weather anomalies persist over the same region for several weeks to months. Though precipitation deficits over some time period are required for drought to develop, their presence alone is unlikely to lead to a flash drought because a lack of precipitation is only one of several factors that can lead to rapid drought intensification. For example, when precipitation deficits occur alongside other weather anomalies that enhance evaporative demand, such as high temperatures, low humidity, strong winds, and sunny skies, they can work together to quickly deplete soil moisture reserves due to increased ET (Otkin et al. 2013; Anderson et al. 2013). Persistence of such conditions for days to weeks can force a transition from energy-limited ET to water-limited ET, leading to rapid increases in vegetation stress and the emergence of flash drought (Hunt et al. 2009, 2014; Mozny et al. 2012; Ford et al. 2015; Ford and Labosier 2017). Because this scenario is most likely to occur during the growing season when evaporative demand is climatologically highest, flash droughts tend to have their largest impact on agriculture (Otkin et al. 2013, 2016; Hunt et al. 2014; Anderson et al. 2016) and natural ecosystems (Crausbay et al. 2017). Perhaps the earliest mention of this type of phenomenon was made by Lydolph (1964) in reference to the Sukhovey, which is a wind accompanied by high temperatures and low relative humidity that originates in central Asia and primarily occurs during the growing season. Though the term refers to the wind rather than to drought, these events lead to rapid wilting of vegetation and have historically had a major impact on agriculture from Eastern Europe to central Asia.

In their introduction to the USDM, Svoboda et al. (2002) coined the term "flash drought" to draw attention to the unusually rapid intensification of some droughts and to better distinguish these events from traditional droughts that develop more slowly. Otkin et al. (2013) examined the salient characteristics of rapid onset flash drought events across the U.S. using the satellite-derived Evaporative Stress Index (ESI; Anderson et al. 2007), which depicts standardized anomalies in a normalized ET fraction given by the ratio of actual ET to potential ET (PET). A detailed analysis of four flash droughts revealed that rapid increases in moisture stress as depicted by rapid decreases in the ESI over several weeks were usually associated with higher air temperatures, fewer clouds, larger vapor pressure deficits, and stronger winds. Given adequate plant available soil moisture (i.e., energy-limited conditions), rapid increases in both evaporative demand and ET will deplete soil moisture. However, if plant available soil moisture approaches the wilting point (i.e., water-limited conditions), such increases in evaporative demand will lead to dramatic decreases in ET and increasing vegetation moisture stress. For example, Hunt et al. (2014) showed that ET from adjacent rainfed and irrigated corn fields diverged significantly after plant available soil moisture in the rainfed crop dropped below 30%. Otkin et al. (2013) also showed that change anomalies depicting how rapidly the ESI is changing with time can provide early warning of flash drought development. Otkin et al. (2014, 2015a) subsequently developed the Rapid Change Index (RCI) to encapsulate the accumulated magnitude of moisture stress changes occurring over multiple weeks. These studies showed that droughts are more likely to develop when the RCI is negative and that this likelihood increases dramatically as the RCI becomes more negative.

Several studies have also examined how soil moisture conditions evolve before and during flash drought events. Hunt et al. (2009) developed a Soil Moisture Index (SMI), which is computed using soil moisture observations and estimated wilting and field capacity soil metrics, to examine changes in moisture stress during a flash drought over Nebraska. A subsequent study by Mozny et al. (2012) in the Czech Republic showed that the SMI provides valuable information about the effectiveness of recent rains that can be used to alert agricultural stakeholders about potential drought development. More recent studies by Hunt et al. (2014) and Ford et al. (2015) using soil moisture observations in Nebraska and Oklahoma, respectively, have shown that soil moisture rapidly decreases during the onset phase of a flash drought due to increased ET and that soil moisture anomalies tend to initially appear in the topsoil layer before moving deeper into the soil profile. A soil moisture deficit coupled with persistently elevated evaporative demand will eventually result in vegetation stress, and the potential development of flash drought. Ford and Labosier (2017) have also recently shown that periods of rapid soil moisture depletion are typically associated with lower precipitation and humidity and increased solar radiation and temperature, which is consistent with the Otkin et al. (2013) study focusing on ET. By using logistic regression, Ford and Labosier (2017) determined that variables accounting for evaporative demand (PET and water vapor pressure deficit) or the balance between supply and demand of surface moisture (precipitation – PET) are better predictors of flash drought development than are temperature or precipitation alone.

A common theme of these studies is the requirement for the root zone soil moisture content to rapidly fall below a threshold associated with vegetation moisture stress for it to be considered a flash drought event. This transition from energy-limited to water-limited conditions is often necessary for soil moisture-atmosphere feedbacks to occur (Seneviratne et al. 2010). It also exemplifies the complex relationship between evaporative demand, soil moisture, and ET. Elevated evaporative demand coupled with initially adequate-to-surplus soil moisture content will result in increased ET and a subsequent depletion of soil moisture reserves. The transition from an energy-limited to water-limited regime occurs when a continuation of enhanced evaporative demand and concurrent decline in root zone soil moisture leads to vegetation moisture stress and a decrease in ET. Therefore, rapidly declining soil moisture content could potentially serve as a precursor for flash drought, particularly if plant available soil moisture is approaching critical levels such as the wilting point. The switch from adequate to deficit soil moisture conditions will also be evident in datasets such as the ESI as the vegetation responds to soil moisture restrictions by decreasing its ET.

In contrast to the above studies that have identified flash droughts based on an unusually rapid rate of intensification, several other studies have instead focused on their duration. For example, Mo and Lettenmaier (2015, 2016) used pentads (5-day periods) to identify flash droughts based on anomalies in modeled soil moisture, precipitation, ET, and temperature. They suggested that there are two types of flash droughts: "heat wave" flash droughts that are driven by high temperatures, and "precipitation" flash droughts that are driven by below normal precipitation. Heat wave flash droughts require temperature anomalies > 1 standard deviation above normal for a given pentad along with positive ET anomalies and soil moisture content below the 40th percentile. Precipitation anomalies for that pentad are allowed to be positive or negative. In this situation, the unusually high temperatures cause evaporative demand to increase, which in turn leads to either decreasing soil moisture in energy-limited conditions where there is adequate plant available soil moisture, or decreased ET in water-limited conditions where soil moisture is insufficient to meet the vegetation's needs. Conditions for heat wave flash droughts are mostly likely to be met across the Midwest and Pacific Northwest where there is dense vegetation. A similar pattern was found by Wang et al. (2016) in which heat wave flash droughts occurred on average twice per year across densely vegetated areas of southeastern China. For precipitation flash droughts, temperature anomalies must again be at least 1 standard deviation above normal with soil moisture below the 40th percentile; however, for these events, precipitation is also required to be less than the 40th percentile and ET anomalies must be negative in order to distinguish them from heat wave flash droughts. In this case, the precipitation deficits lead to below normal ET and above normal temperatures. These conditions occur most often across the southern U.S. Overall, their results show that both types in aggregate occur up to several times each year at a given location, with most events lasting no more than 2 pentads (10 days), thereby making them short, frequent events.

Proposed flash drought definition

As discussed in the previous section, there is currently a lack of consensus in the scientific community concerning the definition of flash drought; namely, whether it should be based on how rapidly a drought develops as originally proposed in Svoboda et al. (2002) or instead be based on its duration? Here, we argue that any definition of flash drought should inherently account for both its rapid intensification (i.e., the flash) and the actual condition of moisture limitation (i.e., the drought). We propose that flash droughts should be viewed as a subset of all droughts that are distinguished from more conventional slowly developing droughts by their unusually rapid rate of intensification. This definition can be seamlessly applied to all types of drought; however, this essay will focus on agricultural and ecological flash droughts given their large impact on crop yields, livestock forage production, and natural ecosystems. By focusing the definition on the development phase of a drought, this means that a flash drought that initially impacts agriculture can ultimately develop into long-term hydrological drought, such as occurred across the central U.S. in 2012. That year, widespread areas experienced a flash drought during the first half of summer that reached its peak intensity by late summer, but then persisted for over a year in some locations following the end of the rapid intensification period. We do not propose that the entire event in such cases should be classified as a flash drought; rather, the term “flash drought” should be reserved for the time period during which the rapid intensification occurred.

Because the proposed flash drought definition focuses on the intensification rate, it is necessary to use metrics depicting changes in some quantity over a period of time to identify a flash drought. It is also important to account for seasonal or regional climate characteristics that may make rapid decreases in soil moisture or some other quantity more or less likely to occur during certain times of the year. This could be accomplished in a variety of ways, such as simply requiring an index expressed as a percentile to decrease by a certain amount over a specified time period. An alternative approach is to use standardized change anomalies that depict how rapidly an index is changing with time relative to the local climatology for that time of the year. The severity of the flash drought could then be determined based on the magnitude of the change anomalies each week or over an extended period of time, similar to the approach used in the RCI. Regardless, a key requirement for identifying a flash drought is to choose a drought index that can respond quickly to rapidly changing conditions. For agricultural and ecological flash droughts, this typically means choosing drought indices computed over short time periods (e.g., < 1 month) that are sensitive to soil moisture, ET, evaporative demand, or vegetation health, and then assessing changes in those indices during the past few weeks (Otkin et al. 2013).

As a second requirement, we propose that the chosen index must actually fall into drought during the rapid intensification period in order for the event to be classified as a flash drought. To be consistent with existing drought definitions, this means that the index must fall below the 20th percentile for the event to be considered flash drought because that is when abnormally dry conditions begin to have a large impact on the environment (Svoboda et al. 2002). By design, this requirement will lead to the exclusion of short periods characterized by rapid deterioration that do not actually lead to drought. Also, by not imposing a starting threshold on the drought index, a flash drought can initially develop even when the index originally depicts near normal conditions. For example, a region containing adequate soil moisture could experience flash drought if large precipitation deficits quickly develop or there is a prolonged period of excessive atmospheric demand that leads to a rapid transition to water-limited conditions and subsequent drought development.

Similar to other drought types, flash droughts are characterized by a range of intensities, with the magnitude of the flash drought and its impacts on both managed and natural ecosystems largely determined by how quickly drought conditions develop, the magnitude of the observed changes, and whether or not long-term drought develops after the period of rapid intensification ends. Therefore, to better capture the full range of flash drought intensities, we propose that a suite of different magnitude and temporal change thresholds rather than a single universal definition should be used to identify them and to characterize their overall severity. For example, with the USDM, a 2-category increase in drought severity over a 6-week period could be used to classify a flash drought as having moderate intensity, whereas a larger 4-category change over a similar time period would represent a more severe flash drought event. Another approach would be to define the flash drought intensity based on the magnitude of standardized change anomalies and their persistence over multi-week periods as is done when computing the RCI (Otkin et al. 2015). Likewise, Ford and Labosier (2017) chose to define flash droughts to be situations when soil moisture percentiles for a given location dropped from above the 40th percentile to below the 20th percentile over a 20-day period. That methodology could be expanded to include additional percentile and temporal change thresholds to capture a broader range of flash drought events. In contrast, Mo and Lettenmaier (2015, 2016) mandate that soil moisture must be below the 40th percentile during a single 5-day period for flash drought to occur. Because their definition does not account for changes in soil moisture with time, nor is the threshold dry enough to actually be considered drought, we argue that their definition does not identify flash droughts and therefore its use should be discontinued.

Monitoring the evolution of a flash drought

Though the general characteristics of individual flash drought events, such as their intensification rate and severity, will vary from one event to another due to differences in the antecedent conditions and the strength and persistence of the atmospheric anomalies driving their evolution, some guidelines regarding their evolution can still be constructed using results from prior studies. Figure 2 provides a schematic overview of a typical flash drought event. To effectively capture the onset and evolution of a flash drought, it is necessary to use a variety of drought monitoring tools depicting anomalies in soil moisture, ET, evaporative demand, and vegetation health. In general, flash drought onset is more likely to occur when the evaporative demand is much higher than normal for several weeks. New drought monitoring tools such as the Evaporative Demand Drought Index (EDDI; Hobbins et al. 2016; McEvoy et al. 2016) can be used to identify regions experiencing excessive atmospheric demand over different time scales and has been shown to provide early warning of flash drought development. A key requirement for a flash drought to develop, however, is that the enhanced atmospheric demand is not compensated for by increased precipitation. Thus, to properly account for deficits in the balance between supply and demand of surface moisture (e.g., precipitation – PET), tools such as the Standardized Precipitation Evapotranspiration Index (Vicente-Serrano et al. 2010) that combine anomalies in precipitation and evaporative demand should be used because assessing each component separately may provide an incomplete indication of drought severity. Indeed, it is the juxtaposition of near to below normal precipitation and above normal evaporative demand that leads to flash drought development.

During the onset phase of a flash drought, soil moisture deficits often develop in the topsoil layer first and then move deeper into the soil column; however, large deficits can also develop over a deeper layer if the vegetation has a deep root structure that can access subsoil moisture. Indeed, to cope with higher atmospheric demand, vegetation often accelerates flash drought development through a more rapid depletion of root zone soil moisture due to enhanced ET. Satellite microwave sensors sensitive to soil moisture in the top 5 cm of the soil profile provide valuable information about drought onset, albeit with coarse horizontal resolution (25-40 km) and with limited direct information about root zone moisture. Because of this, soil moisture monitoring networks and land surface models that provide soil moisture information over the entire root zone are critical for flash drought detection. Though ET may initially be enhanced due to high evaporative demand, vegetation will begin to curtail its water usage as the soil moisture continues to decrease, thereby leading to water-limited conditions. Because ET anomalies may change sign from positive to negative during the onset of a flash drought, a clearer signal of the worsening conditions can be obtained using tools such as the ESI that depict anomalies in the potential ET fraction (ET / PET). Tools such as the ESI and EDDI are complementary to each other because drought signals often emerge earlier in EDDI, but at the expense of a high false alarm rate because not all regions with unusually high evaporative demand will experience drought. The ESI can be used to better delineate which areas within a broad region of increased evaporative demand are actually experiencing moisture stress conditions. This is aided by the coupling between increased moisture stress and elevated land surface temperatures observed in the thermal infrared imagery used to compute the ESI. As flash drought conditions continue to intensify, large soil moisture deficits develop over a deep layer of the soil column and often display a similar temporal evolution to the ESI given the tight coupling between soil moisture and ET.

As drought conditions become more severe, visible signs of moisture stress such as yellow or curled leaves become more apparent in the vegetation. These visible signs of deterioration tend to occur after the initial decreases in soil moisture and ET and are associated with decreases in leaf area index, gross primary productivity, and vegetation fraction. During severe drying, whereby the available water in the root zone is fully depleted, the vegetated canopy can experience temporary or permanent senescence, a dramatic reduction in ET, and due to the loss of evaporative cooling via ET, localized thermal anomalies that further perpetuate drought conditions via elevated sensible heating. A representative example illustrating the rapid deterioration of vegetation health during a flash drought is shown in Fig. 3 using phenocam images from the Marena, OK in situ sensor testbed (MOISST; Cosh et al. 2017). In this example, the 2012 flash drought caused the grasses to rapidly brown and go dormant over a 6-week period, which stands in sharp contrast to the continued greenness over the same time period in 2014. A wide assortment of satellite-derived tools, such as the Normalized Difference Vegetation Index (Tucker 1979), Enhanced Vegetation Index (Huete et al. 2002), or Land Surface Water Index (Xiao et al. 2002) computed using visible and near infrared satellite imagery can be used to provide high-resolution estimates of vegetation health during flash drought events.

To summarize, a typical progression during either an agricultural or ecological flash drought given adequate-to-surplus soil moisture (i.e., energy-limited regime) is for an extended period of enhanced evaporative demand to initially cause an increase in ET as vegetation responds to the anomalous weather conditions, subsequently followed by a period of rapidly decreasing soil moisture content, a transition to water-limited conditions, reduced ET, and the subsequent emergence of visible signs of vegetation moisture stress. The intensification rate and final severity of a flash drought will be strongly influenced by the strength and persistence of the atmospheric anomalies forcing its evolution, the magnitude of the precipitation deficits, and the vulnerability of the crops or rangelands to drought. After the period of rapid intensification ends, a flash drought could potentially develop into hydrological drought or simply be terminated by a heavy precipitation event.

Concluding remarks

Though the term "flash drought" first entered the scientific lexicon in the early 2000s to describe droughts that intensify more rapidly than conventional droughts, it did not become popularized until 2011 and 2012 when the media and scientific community began to extensively use the term when referring to the devastating droughts that affected parts of the central U.S. each of those years. Given its continued widespread use in the media to describe more recent droughts and its increasing use in journal articles, it is prudent to develop clear and consistent terminology that allows us to more effectively convey the characteristics of these events and the risks they may pose to vulnerable stakeholders. In recent years, however, two separate approaches have been used to identify flash droughts: one that focuses on the rate of intensification and another that focuses on duration. These conflicting notions for what constitutes a flash drought – rapid development versus short duration – introduce ambiguity that affects our ability to detect their onset, monitor their development, and forecast their evolution and demise.

Here, we have proposed that the definition for flash drought should inherently focus on its rate of intensification rather than its duration, with droughts that develop more rapidly than normal being identified as flash droughts. By focusing on their unusually rapid rate of intensification, the definition clearly highlights their most salient characteristic. Given the spate of rapid onset flash droughts in recent years and their large impact on farming and ranching, there is also an urgent need to enhance our ability to forecast these events. To capture their rapid onset, it is necessary to generate drought intensification forecasts at weekly intervals that depict changes in drought conditions over sub-seasonal time scales. In addition to improvements to climate models, new empirical forecasting methods such as those presented by Lorenz et al. (2017a, b) that leverage the long-term memory of soil moisture and vegetation should be explored. Studies that increase our understanding of the role that atmosphere–land surface interactions play during flash drought development and the ability of land surface and climate models to depict their onset and evolution are also necessary. Finally, as discussed in Otkin et al. (2015b), stakeholder groups vulnerable to flash droughts desire monitoring and forecasting tools that are easy to use and deliver timely information. Having a consistent definition for what constitutes a flash drought enhances our ability to provide stakeholders useful information and promotes a more thorough understanding of these important features of the climate system.

Acknowledgments

The authors would like to acknowledge support provided by the NOAA Climate Program Office (CPO) Modeling, Analysis, Predictions, and Projections program under grant NA14OAR4310226, the NOAA CPO Sectoral Applications Research Program under grants NA16OAR4310130 and NA13OAR4310122, and the USDA National Institute of Food and Agriculture under grant number 2013-69002-23146. The authors also want to thank two anonymous reviewers and the editor for their thorough reviews that helped improve the clarity of the manuscript.

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Figure Captions

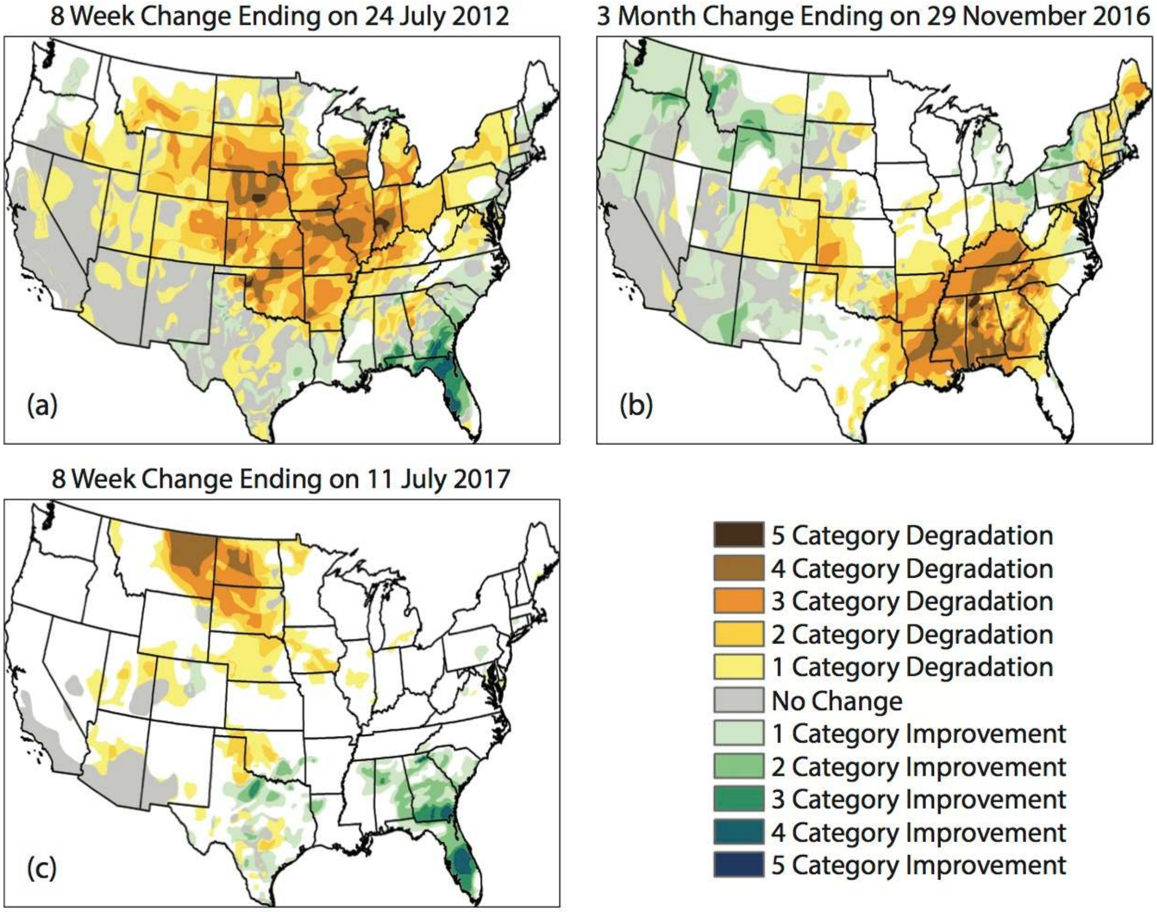
Figure 1. Three examples illustrating rapid drought intensification, including (a) 8-week change in the USDM ending on 24 July 2012, (b) 3-month change in the USDM ending on 29 November 2016, and (c) 8-week change in the USDM ending on 11 July 2017. The dark orange and brown colors indicate regions where flash drought occurred as signified by the large increases in drought severity over the specified time period. Change images

were obtained from the National Drought Mitigation Center.

Figure 2. Schematic overview showing the typical evolution of a flash drought event. The schematic is based on Fig. 11.3 in Hobbins et al. (2017).

Figure 3. Phenocam images taken at the Marena, OK in situ sensor testbed (MOISST) adjacent to the Marena Oklahoma Mesonet station on (a) 01 July 2012, (b) 11 August 2012, (c) 01 July 2014, and (d) 11 August 2014. All images were taken at 10:30 AM local time.

Figures



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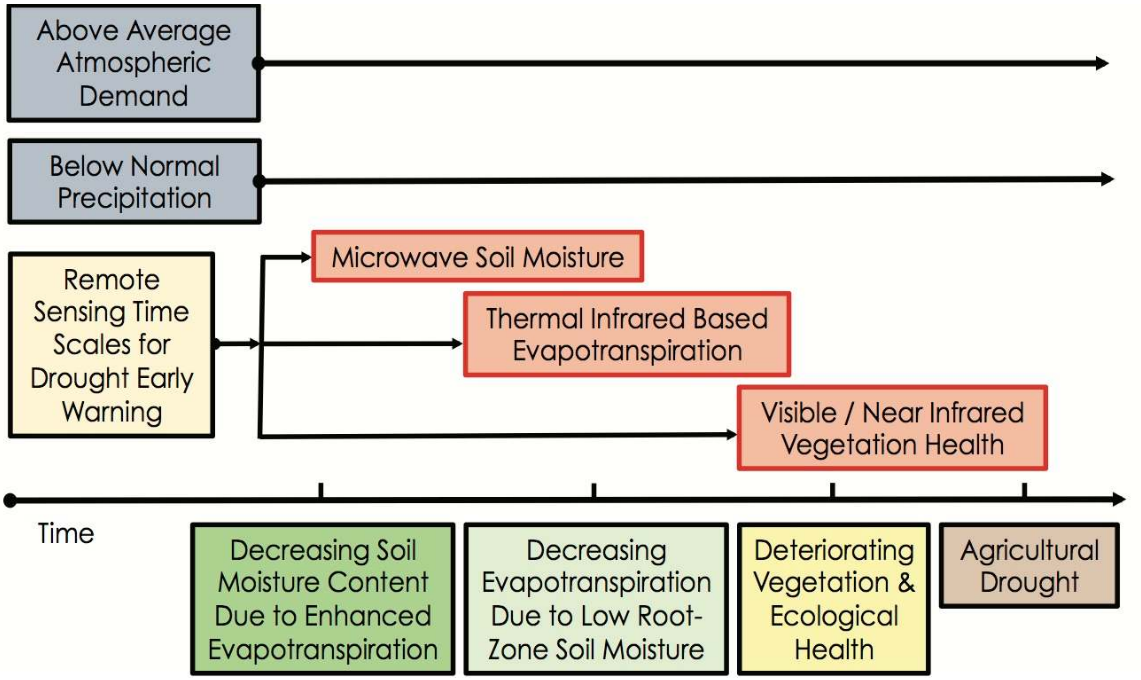

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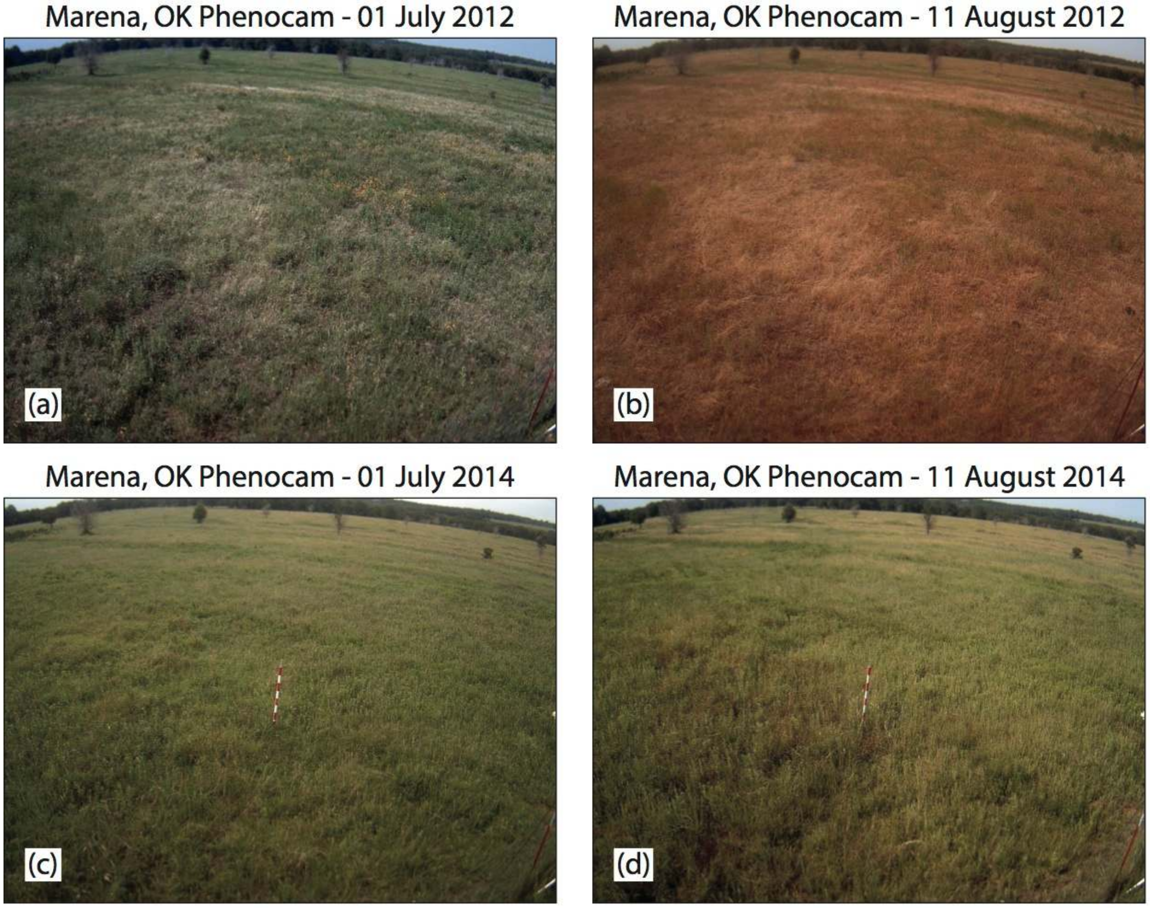

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