Flash Drought Literature Review

National Oceanic and Atmospheric Administration—National Integrated Drought Information System (NIDIS)

Abstract

To prepare for the upcoming Flash Drought Workshop, NIDIS has composed this review of flash drought research, focused on the use and definition of the term "flash drought." We found that the term first appeared in the peer-reviewed literature in 2002, and by 2020 has become an area of active research. Within that 18-year span, "flash drought" has been given 16 general descriptions, and 19 papers have provided measurable, defining criteria used to distinguish a flash drought from other drought. Of these papers, 11 distinguish flash drought as a rapid-onset drought event while seven distinguish flash drought as a short-term or short-lived, yet severe, drought event and one paper considers flash drought as both a short-lived and rapid onset event. Of the papers that define a flash drought by its rate of onset, the rate proposed ranges from 5 days to 8 weeks. Currently, there is not a universally accepted definition or criteria for "flash drought," despite recent research that has called for the research community to adopt the principle of rapid-intensification of drought conditions.

Motivation and Methodology

Flash drought has been the topic of scientific research since 2002. Research on this topic has increased exponentially because of a flood of publications since 2015 (Figure 1). As of July 2020, there have been over 35 publications wholly devoted to the topic and at least 35 others that mention the term "flash drought" in relation to other topics. Within these publications, unique defining criteria have been applied to flash drought at least 19 times. Currently, there is not a universally accepted definition or criteria for flash drought, though the principle of rapid intensification that ends in drought is generally applied (Otkin et al. 2018).

In December 2020, NIDIS will host a virtual workshop on flash drought, which will bring together subject-matter experts and other interested researchers to discuss this emerging topic. With direct engagement from attendees, this workshop will discuss the current science of flash drought, provide an opportunity to share perspectives on how to improve our physical understanding of this phenomenon, and explore from a research perspective the best path forward to improve flash drought early warning and preparedness.

One of the desired outcomes of this workshop is to document current flash drought definitions and the advantages/disadvantages of each for research, monitoring, prediction, decision-making, and other specific applications. This will include striving for agreement on the basic set of principles or standards to which definitions of flash drought should adhere and categorizing "most useful" flash drought definitions by sector, region, and application.

To prepare the workshop attendees for this discussion, NIDIS has composed this literature review of flash drought research, focused on the use and definition of the term "flash drought." Following the methodology of Pickering and Byrne (2014), this review began with a SCOPUS search for any papers that included the words "flash drought" in the article title, abstract, or keywords. This search produced 52 unique results (in July 2020). Twenty additional papers were added to these results based on papers

referenced within these articles and further input from subject matter experts. In addition to the refereed journal publications, these 72 total citations included one magazine article, one book chapter, and three conference papers. For perspective and completeness, we also searched for the combined terms "rapid onset" + "drought," "rapid development" + "drought," "rapid intensification" + "drought," "short-term" + "drought,"[1] and "short-duration" + "drought." This produced 203 total results, including 167 irrelevant results (e.g. economics, engineering, botany, etc.), 31 duplicate results to the "flash drought" search, and six papers that are included in the final literature review.

A Brief Timeline of Flash Drought Research Highlights

First References

In 1999, R. Showstack authored a piece for *EOS, Transactions*[2] titled, *US federal government tries to get ahead of the curve with drought planning,* in which prominent physical scientists were interviewed about drought. Showstack (1999) points to the slow onset of drought compared to more dramatic and sudden weather events and states "Droughts receive less attention because they are slow-moving disasters... There is no such thing as a flash drought, for instance, and droughts edge up without lightning bolts or tremors that people experience directly."

Showstack (1999) notwithstanding, the term "flash drought" began showing up in the published literature only three years later. First, in January 2002 by Peters et al. (2002)—a paper on the derivation and utility of the Standardized Vegetation Index (SVI)—that points to the rapid intensification of drought across the southern High Plains in August and September 2000 and says, "the term to describe this was 'flash drought' because of the combination of no precipitation and very high temperatures," likely alluding to discussions about the event that were occurring outside of the published literature at the time. The term appeared again in August 2002 in the seminal paper on the Drought Monitor by Svoboda et al. (2002), where "flash drought" was mentioned in a general reference to rapidly intensifying drought conditions.

Both Svoboda et al. (2002) and Peters et al. (2002)[3] have been referenced as the first use of the term "flash drought." Svoboda et al. (2002) has been cited by several authors including the Otkin et al. (2018a) review paper on the topic (also see Hunt et al. 2014; Otkin et al. 2015; McEvoy et al. 2016). Peters et al. (2002) was referenced by Twidwell et al. (2014) and Lee and Gill (2015).

First General Definitions

The earlier references to flash drought were general in their description. For example, Svoboda et al. (2002) describes flash drought as "rapid crop deterioration due to the adverse effects of a severe heat wave and short-term dryness, leading to a rapid onset of drought and associated impacts..." The first place to offer a definition of flash drought (and specifically call it a definition) was a conference presentation at the AMS 22nd Conference on Hydrology in 2008. Here Senay et al. (2008) defined flash drought as "a short-term, yet severe [drought] event, characterized by moisture deficits and abnormally

[1] The search "short-term" + "drought," produced 2,541 results, so in this case we refined our search to also include "flash drought" somewhere in the text.

[2] *EOS, Transactions* was a weekly magazine of Earth science published by John Wiley & Sons for the American Geophysical Union (now available online only at eos.org).

[3] Svoboda was a co-author on the Peters et al. (2002) paper.

high temperatures." The Senay et al. (2008) drought definition has been referenced directly twice by subsequent authors (Hunt et al. 2009; Mozny et al. 2012).

First Paper to Define Flash Drought Using Indicator Values and a Defining Criterion

Hunt et al. (2009) was the first paper to use a set of criteria to objectively determine a flash drought. With a reference to Senay et al. (2008), they defined a flash drought as "a severe, short-term [drought] event characterized by moisture deficits and abnormally high temperatures." Hunt et al. (2009) further add that "a flash drought is the result of a synoptic meteorological pattern where potential ET (evapotranspiration) greatly exceeds precipitation for a period no less than 3 weeks such that available water in a previously moist (0–50 cm) soil profile decreases by more than 50%."

First Paper to Solely Focus on Flash Drought

The first paper solely devoted to the topic of flash drought was Otkin et al. (2013), which examined the characteristics of the following four "rapid-onset droughts": Oklahoma and Arkansas in late summer 2000; Indiana and Ohio in early summer 2007; Southeast Wisconsin in summer 2002; and Oklahoma and Arkansas in summer 2011. This paper used the terms "rapid-onset drought" and "flash drought" interchangeably. This paper demonstrated that the Evaporative Stress Index (ESI) is effective in providing early warning of flash drought events. While they did not explicitly define flash drought, they referred to Mozny et al. (2012) in their description of flash drought. (Note: in their description of flash drought, Mozny et al. [2012] referred to Senay et al. [2008], which was the first research to offer a definition of the term, as noted above).

Flash Drought Research and the 2012 Drought

Between 2002 and 2012 the literature was seemingly quiet on the topic of flash drought. It is possible that there were papers published on the topic during this time that simply did not use the term "flash drought" but rather stayed within the accepted terminology of the time. Two possible examples of this are Fowler and Kilsby (2002) and Illston et al. (2004). Fowler and Kilsby (2002) mention "rapid onset of recent drought" in the Yorkshire region of the UK, but do not use the term "flash drought." This paper was found in the search for "rapid onset" + "drought." Illston et al. (2004) was found as a reference in Hunt et al. (2014). This paper examines rapid changes in the soil moisture profile in Oklahoma, USA, before and after the 2000 drought, but they do not call it a "flash drought.". Any other similar papers would not have shown up in our literature search and are not included in this review, which is focusing on the use and definitions of "flash drought." Even the use of additional search terms ("rapid onset" + "drought," "rapid development" + "drought," etc.) did not yield any papers that were published between 2002 and 2012, other than Fowler and Kilsby (2002).

The rate of flash drought publications increased after 2012 (see Figure 1). One reason for this increase is the extreme drought over the central US during 2011 and 2012. During this time, the term seemed to be picked up by both the media and the scientific community in the United States (Otkin et al. 2018a). According to many publications, the 2012 drought in the US Central Plains was a quintessential flash drought[4] and has been used as a case study by many (Hoerling et al. 2013, 2014; Kumar et al. 2013; AghaKouchak 2014; Otkin et al. 2014, 2015b; Behrangi et al. 2015; Mo and Lettenmaier 2015; Wang et

[4] One exception is McEvoy et al. (2016) which demonstrates the application of the Evaporative Demand Drought Index (EDDI) for detecting and monitoring flash drought and challenges the notion that 2012 should be considered a flash drought, at least over central Iowa.

al. 2015; Sun et al. 2015; PaiMazumder and Done 2016; Otkin et al. 2016; Lorenz et al. 2017a,b; Yan et al. 2018; Jin et al. 2019; Sun et al. 2019; Basara et al. 2019) or as a flash drought standard against which to compare other droughts (He et al. 2019). While there had been flash droughts before the 2012 event (e.g., 2000 in the Southern US), the 2012 event certainly attracted researchers' attention to the topic.

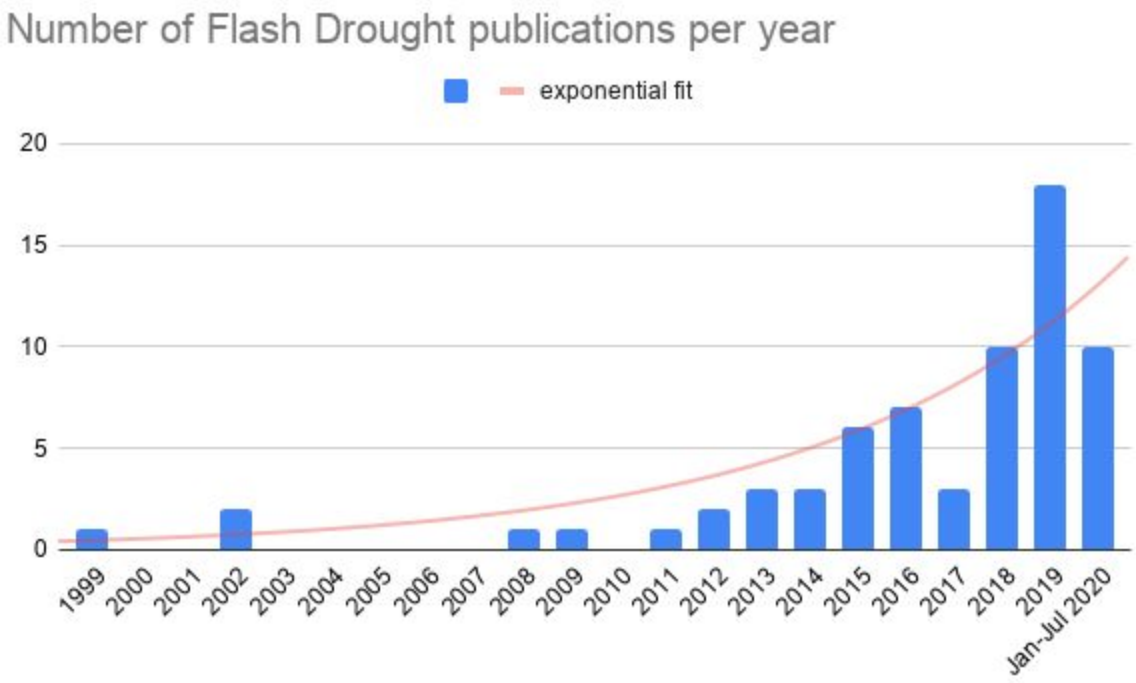

Figure 1: Publications on Flash Drought each year have increased approximately exponentially since the first reference 1999.

Definitions

Flash drought has been defined in at least 36 different ways, although several definitions[5] are closely related or add qualifiers to previously proposed definitions. This section documents all of these definitions or descriptions and the criteria used by each definition. Where a definition is used in multiple papers, we include only its first instance, and note who refers to that definition in subsequent research.[6] We chose to group these definitions into the following categories: (1) general definitions that provide a qualitative description of flash drought but provide neither criteria nor thresholds to measure or distinguish flash drought events; (2) definitions based on the rate of onset; (3) definitions based on duration of the drought event or that, by nature of the criteria used, can distinguish a flash drought as one with a short duration; (4) definitions based on both the duration and the rate of onset to identify a flash drought (one paper).

[5] While we use the word "definition," in some instances the authors only provide a description of the term "flash drought." We are including these papers here for completeness.

[6] A full list of papers identified are included in the references section.

General Definitions or Descriptions

Sixteen papers provided a general description of flash drought (Table 1). While some papers may describe flash drought in terms of rate of onset or duration, they do not provide specific thresholds that could be used to distinguish flash droughts.

One notable inclusion here is Otkin et al. (2018a), which provided a review and assessment of flash drought science up to 2018. The authors proposed that flash drought is ‘‘a subset of all droughts that are distinguished… by their unusually rapid rate of intensification.’’ However, it did not specify how rapid the rate must be to be considered “unusual,” i.e. they did not provide a definition based on thresholds of an indicator(s). Rather, the authors proposed a set of guiding principles that should be considered when examining flash drought. A criteria-based definition was proposed by Christian et al. (2019a) based on the recommendations made by Otkin et al. (2018a) and will be discussed briefly in the next section.

Table 1: List of generalized flash drought descriptions in chronological order.

Reference	Generic Descriptions
Peters et al. (2002)	"flash drought...combination of no precipitation and very high temperatures..." *Referenced by Lee and Gill (2015); Twidwell et al. (2014)*
Svoboda et al. (2002)	"flash drought...refers to rapid crop deterioration due to the adverse effects of a severe heat wave and short-term dryness, leading to a rapid onset of drought and associated impacts in agriculture, fire potential, livestock health, and other areas." *Referenced by Hunt et al. (2014); McEvoy et al. (2016); Otkin et al. (2018a)*
Senay et al. (2008)	"A flash drought is considered to be a short-term, yet severe event, characterized by moisture deficits and abnormally high temperatures." *Referenced by Hunt et al. (2009); Mozny et al. (2012) [*Mozny et al. (2012) *is then referenced by* Otkin et al. (2013)*]*
Anderson et al. (2011)	"…the so-called flash drought events, where prolonged hot, dry, and windy conditions lead to rapid water loss and the potential for catastrophic crop yield loss."
Hunt et al. (2014)	“Short-term drought, sometimes referred to as flash drought, is a rapid onset of drought often accompanied by high temperatures and winds that lead to rapid soil moisture depletion during a critical time in the growing season (Svoboda et al., 2002).”
Otkin et al. (2015a)	"…the term ‘flash drought’ has been used to better distinguish rapid-onset drought events from those that develop more slowly (e.g., Otkin et al. 2013; Svoboda et al. 2002). This Terminology captures the distinguishing characteristic of these droughts, namely, their unusually rapid rate of intensification."
Sun et al. (2015)	“...the 2012 drought in the central Great Plains was preceded by relatively normal precipitation and warmer surface temperature in spring followed by an abrupt rainfall reduction and abnormally high temperatures in summer, typifying a “flash” drought (Hoerling et al., 2014; Mo and Lettenmaier, 2015).”
Anderson et al. (2016)	“rapid onset – or ‘flash’ – drought events.”
Hobbins et al. (2016)	“’Flash Drought’...i.e., fast-developing drought driven by strong, transient meteorological/radiative changes—such as increases in T_{air}, wind, or radiation, or decreases in humidity—with no substantive change in Prcp.”
Yao et al. (2018)	Generally regarded flash drought as a rapid-onset drought event.
Otkin et al. (2018a)	Flash Drought: ‘‘a subset of all droughts that are distinguished from more conventional slowly developing droughts by their unusually rapid rate of intensification.’’ *Referenced by (Otkin et al. 2018b, 2019; Basara et al. 2019; Nguyen et al. 2019; He et al. 2019; Haigh et al. 2019; Christian et al. 2019a, b)*
Lorenz et al. (2018)	Generally: "if the US Drought Monitor is more intense in [2, 4, or 6] weeks" then the authors considered this a rapid onset to the drought situation.

Gerken et al. (2018)	Described "rapid onset" droughts, and in the case study used the Northern Great Plains 2017 drought which set in over 2-to-4 months depending on the location.
Hoell et al. (2019)	Described the 2017 Northern Great Plains drought as a "rapid" decrease in soil moisture, leading to agricultural drought that ended g "just three months after it began."
Jin et al. (2019)	"The 2012 flash drought in the US Midwest, [was] characterized by high temperature, large cumulative rainfall deficit, and rapid depletion of soil moisture..."
Zhang et al. (2020)	"Flash drought is a short-term drought event that develops rapidly in association with a high-temperature heat wave. It occurs suddenly with fast development and high intensity, posing a serious threat to crop yield and water supply."

Rate vs. Duration

As mentioned above, we could have grouped these definitions in various ways, but the literature includes a subtle debate about whether flash drought should be defined by the rate of onset/intensification or the duration of the drought event, and we have chosen this grouping to bring this debate to the forefront.

The Senay et al. (2008) definition references "short-term, yet severe" events that last at least three weeks but are not required to last longer than that. This idea of a "short-term" drought was supported by Mo and Lettenmaier (2015, 2016) who proposed that there are two types of flash drought, a "heat wave flash drought" and a "precipitation deficit flash drought." While the precise definitions proposed by Mo and Lettenmaier (2015, 2016) do not have a duration requirement, the nature of their proposed definition relying on a heat wave means that these *flash drought* events will be short-lived. Therefore, they conclude that "One feature that distinguishes flash droughts from longer meteorological and agricultural droughts is that flash droughts generally do not persist because T_{air} anomalies tend not to be persistent. For heat wave flash droughts, most events only last for one to two pentads." (Mo and Lettenmaier 2016).

The Otkin et al. (2018a) review paper on the topic weighed in heavily on this debate, stating: "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 much more rapidly than normal being identified as flash droughts." Under this definition, even droughts that persist for several years may be considered a flash drought, (e.g. Southeast Australia 2017-2020 drought, see Nguyen et al. 2019).

Rate of Onset Definitions

Eleven papers in our review define flash drought by its rate of onset or intensification that are tied to specific thresholds of various indicators (Table 2).

Table 2: List of flash drought definitions based on the rate of onset, in chronological order.

Reference	Onset rate criteria
Anderson et al. (2013)	*Flash drought* was not explicitly defined, but the authors looked for periods when changes in Evaporative Stress Index (ESI) and Soil Moisture (SM) occurring over a 4-week interval were strong (>1.5 standard deviations).
Ford et al. (2015)	"We define a flash drought event in the USDM record as three category or more increase in drought severity over 8 or less weeks."
Ford and Labosier (2017)	Flash Drought is when "the pentad-average 0–40 cm soil moisture percentile at a station declines from at or above the 40th percentile to at or below the 20th percentile in 4 pentads or less."

Park et al. (2018)	Examined three satellite-based drought indices (details given in the paper): 1. The scaled drought condition index (SDCI) 2. Microwave integrated drought index (MIDI) 3. Very short-term drought index (VSDI), When any of these three indices dropped below 0.4 for even only one pentad (5 day period), the authors considered this a "dry period". While the authors did not define "flash drought", they conclude that the VSDI would be good for identifying "flash droughts caused by a rapid rate of intensification."
Koster et al. (2019)	Based on Ford and Labosier (2017) definition but with the following additional constraints: 1) "A drought event has to lead to at least a nominal reduction in ET and thereby reflect some moisture stress on the land system…The 'nominal reduction' enforced here focuses on ET in the 20 days prior and in the 20 days after the 20-day soil moisture reduction period—ET in the prior period must lie at or above four-fifths of the climatological mean value for that time of year..., and ET in the latter period must lie at or below three-fifths of the climatological mean value for that later time of year." 2) "Independence of drought events is ensured by not allowing identified drought events...to overlap in time." 3) "The final constraint is that the climatological ET during the 20-day soil moisture reduction period lies above 0.5 mm/day. This condition is imposed because ... soil moisture percentile in dry regions is overly sensitive to meteorological drivers."
Christian et al. (2019a)	Based on the principles outlined in (Otkin et al. 2018a): The data used include pentad values of Standardized Evaporative Stress Ratio: SESR = ET/PET which is standardized for each grid point and pentad using the z-score minus the mean and the difference divided by the standard deviation. In this methodology, flash drought events are required to have: 1) a minimum length of five SESR changes (ΔSESR), equivalent to a length of six pentads (30 days); 2) a final SESR value below the 20th percentile of SESR values; 3) pentad-to-pentad changes toward drought development: a) ΔSESR must be at or below the 40th percentile between individual pentads, and b) no more than one ΔSESR above the 40th percentile following a ΔSESR that meets criterion 3a; 4) development through the entirety of the flash drought event...[i.e.] the mean change in SESR during the entire length of the flash drought must be less than the 25th percentile of the climatological changes in SESR for that grid point and time of year. *Referenced by Christian et al. (2019b); Basara et al. (2019)*
Chen et al. (2019)	"[W]e define a flash drought event as a drought event with greater than or equal to two categories degradation in a four-week period based on USDM."
Yuan et al. (2019)	Flash Drought is identified when "the pentad (5 days) mean root-zone (top 1 m) soil moisture decreases from above 40th percentile to 20th percentile, with an average decline rate of no less than 5% in percentile for each pentad...if the declined soil moisture rises up to 20th percentile again, the drought terminates...the drought should last for at least 3 pentads (15 days)."
Liu et al. (2020a)	A drought event (of any kind) is identified when the soil moisture falls below the 40th percentile, and at some point, within the drought event the soil moisture must fall below the 20th percentile (as in Ford and Labosier 2017).

	A *flash drought* event is identified using a Rate of Intensification index (RI), which is the rate of change in soil moisture percentiles (P) per week. RI is measured during the onset-development phase of any drought. A flash drought is defined as: mean RI > 6.5 P/week, or max RI > 10 P/week *Referenced by Liu et al. (2020b)*
Pendergrass et al. (2020)[7]	• **Flash drought definition 1** (applications: international operations, prediction, research): 50% increase in EDDI (toward drying) over two weeks, sustained for at least another two weeks • **Flash drought definition 2** (application: US operations): two-category change in the U.S. Drought Monitor (USDM) in 2 weeks, sustained for at least another 2 weeks
Noguera et al. (2020)	Using the Standardised Precipitation Evaporation Index (SPEI; Vicente-Serrano et al. 2010), they stated: "...the criteria selected to record the occurrence of a flash drought were: 1. A minimum length of 4 weeks in the development phase. 2. A ΔSPEI value equal to or less than –2 z-units. 3. A final SPEI value equal to or less than –1.28 z-units."

The rate of flash drought development depends on the definitions and criteria used in the publications, with onset rates ranging from five days to eight weeks. Table 3 compares the onset rates for each of the definitions listed in Table 2.

Table 3: Comparison of onset rates from papers that defined flash drought as a "rapid-onset" event.

Onset rate	References(s)
5 days	Park et al. (2018)
1 week	Liu et al. (2020a)
2 weeks	Pendergrass et al. (2020)
15 days	Yuan et al. (2019)
20 days	Ford and Labosier (2017); Koster et al. (2019)
4 weeks	Anderson et al. (2013); Chen et al. (2019); Noguera et al. (2020)
30 days	Christian et al. (2019b)
8 weeks	Ford et al. (2015)

[7] These proposed definitions were developed by the attendees of the Aspen Global Change Institute (AGCI) workshop that took place in September 2018.

Short-Duration Drought Events

Of the sixteen general definitions listed in Table 1, three described flash drought as a short-term drought event (Senay et al. 2008; Hunt et al. 2014; Zhang et al. 2020) and a fourth paper (Svoboda et al. 2002) describe "...short-term dryness, leading to a rapid onset of drought." In addition to the general descriptions listed in Table 1, seven papers provided a set of criteria that defined a flash drought to be one that is short-lived (Table 4). While only one of the definitions listed in Table 4 includes short-duration as a defining criteria of a flash drought (Li et al. 2020c), they all consider flash drought to be short-term drought events by nature of the criteria used. Two examples illustrate this: Zhang et al. (2019) defined flash drought in terms of rainfall deficit at a specific time of the year at Shanchuan, China; a "flash-drought event is defined as when the monthly (July or August) rainfall is less than 100 mm." The second example is from Mo and Lettenmaier (2015, 2016) where they require a flash drought to be associated with a heat wave. Mo and Lettenmaier (2016) acknowledge that "Because heat waves do not persist, most flash droughts only last one or two pentads." Hence, we have included these, and similar definitions (Zhang et al. 2017; Yuan et al. 2018; Wang and Yuan 2018;) in the *short-duration drought event* category.

As an aside, most authors who considered flash drought to be a short-term drought event also considered flash drought to be a subset of agricultural droughts. Hunt et al. (2014) and Svoboda et al. (2002) both mention agricultural impacts in their description of flash drought, especially when the short-term dryness corresponds with sensitive times in a crops' development. Mo and Lettenmaier (2015) described a Heat Wave Flash Drought (see Table 4 for a description) as "agricultural drought in nature." Mo and Lettenmaier (2016), when comparing the Heat Wave Flash Drought and the Precipitation Deficit Flash Drought (see Table 4) explain, "Both are manifested by [soil moisture] deficits that cause damage to crops. In that sense, both are agricultural droughts." Zhang et al. (2017) state that "soil moisture deficit is an important indicator of flash drought, and soil moisture is the proximate determinant of agricultural drought, therefore, flash drought is the category of agricultural drought." Wang and Yuan (2018) cite Mo and Lettenmaier (2015) when they write "flash drought is an agricultural drought in nature."

Table 4: List of flash drought definitions that consider only short-term drought events, in chronological order.

Reference	Short-duration criteria
Mo and Lettenmaier (2015)	**Heat wave flash droughts**: T_{air} anomaly > one standard deviation computed from the base period for that pentad, ET anomaly > 0, and Soil Moisture %ile < 40. *Referenced by Mo and Lettenmaier (2016); Zhang et al. (2017); Wang and Yuan (2018); Ran et al. (2020); Zhang et al. (2020)*
Mo and Lettenmaier (2016)	**Precipitation deficit flash drought**: T_{air} anomaly > one standard deviation; ET anomaly < 0, Precip %ile < 40% Applies only to grid points with pentad Precip climatology greater than 0.2 mm/day to distinguish P-deficit flash droughts from monsoon onset conditions. *Referenced by Zhang et al. (2017); Wang and Yuan (2018), Ran et al. (2020); Zhang et al. (2020)*

Zhang et al. (2017)	Adapted from Mo and Lettenmaier (2015, 2016) For each grid and pentad: ● a *Heat Wave Flash Drought event* is defined as the conditions under which the maximum temperature anomaly is greater than one standard deviation, the evapotranspiration anomaly is in positive phase, and the soil moisture percentile is lower than 40%; ● a *Precipitation Deficit Flash Drought* event is defined by maximum temperature anomaly greater than one standard deviation, evapotranspiration anomaly in negative phase, and precipitation percentile below 40% *Referenced by Zhang et al. (2018); Li et al. (2020b)*
Yuan et al. (2018)	For each grid point and each pentad, a flash drought is defined as pentad-mean surface air temperature anomaly is larger than one standard deviation, the percentile of target pentad-mean soil moisture is lower than 40%, and the soil moisture percentile of target pentad is at least 10% lower than the preceding pentad.
Wang and Yuan (2018)	Adapted from Mo and Lettenmaier (2015, 2016) Defined two types of f*lash drought:* (1) FD Type I : $T_{ano} > T_{std}$, $ET_{ano} > 0$, $q(\theta_{pentad}) < 30\%$ (2) FD Type II : $T_{ano} > T_{std}$, $ET_{ano} < 0$, $q(\theta_{pentad}) < 30\%$ Where: T_{ano} (◦C) = anomaly for the pentad-mean surface air temperature T_{std} (◦C) = standard deviation of the T_{ano} time series ET_{ano} (mm/d) = anomaly for the pentad-mean ET $q(\theta_{pentad})$ = pentad-mean soil moisture quantile values (%)
Zhang et al. (2019)	This definition was created specifically for Shanchuan town, Anji County, Zhejiang Province, China, based on the local seasonality and climatology of rainfall at that location. It provides an example of a locally adapted definition of *flash drought.* "A flash-drought event is defined as when the monthly (July or August) rainfall is less than 100 mm"
Li et al. (2020c)	While not using the term “flash drought” this paper references other flash drought papers to define “...short-term droughts lasting a few weeks or even days (Mo and Lettenmaier 2015, 2016; Ford et al. 2015; Otkin et al. 2015, 2016, 2018).” Using the standardized antecedent precipitation evapotranspiration index (SAPEI) this paper defines a “short-term drought” during the growing season (April–September) as: 1. grid points with daily SAPEI <-1 2. The area with SAPEI <-1 covers at least 1.6% of the study region. 3. Drought patches that overlap from one day to the next were considered one event. 4. The total event lasts for 2–4 weeks

Rapid Onset and Short Duration Drought Definition

There was one paper that included both a rate of onset and a short-duration criteria to identify a flash drought (Table 5). Li et al. (2020a) used a standardised evapotranspiration deficit index (SEDI) to identify flash drought using the following three criteria: (1) the duration is longer than five pentads but shorter than twelve pentads; (2) the instantaneous intensification rate of the cumulative SEDI is at or below the 25% of cumulative distribution frequency of the change in the cumulative SEDI during flash drought development; (3) the average instantaneous intensification rate during flash drought development

phase is at or below the 40% of cumulative distribution frequency of the change in the cumulative SEDI during flash drought development.

Table 5: List of flash drought definitions that require a flash drought event to have both a rapid-onset and a short-duration.

Reference	Rapid-onset and short-duration criteria
Li et al. (2020a)	Using a standardised evapotranspiration deficit index (SEDI) flash drought identification follows four criteria: ● The duration is longer than five pentads but shorter than twelve pentads. ● The drought area must be larger than 1.6% of the area of interest, and the area experiencing drought must overlap by at least 50% with the drought area in the previous pentad. ● The instantaneous intensification rate of the cumulative SEDI is at or below the 25% of cumulative distribution frequency of the change in the cumulative SEDI during flash drought development. ● Average instantaneous intensification rate during flash drought development phase is at or below the 40% of cumulative distribution frequency of the change in the cumulative SEDI during flash drought development.

Indicators Used in Flash Drought Definitions

The indicators used in flash drought definitions vary by paper. In this section we have grouped flash drought criteria by indicator used, which also may give an indication of the type of drought described (meteorological, agricultural, hydrological, socioeconomic and ecological; see Otkin et al. 2018a). We will first look at which papers rely upon the US Drought Monitor changes (Svoboda et al. 2002), as the US Drought Monitor is produced through expert examination of a myriad of data sources. We then will look at the indicators used by other papers.

The US Drought Monitor in Flash Drought Definitions

There were four papers that defined flash drought using category changes in the US Drought Monitor as a way to identify a flash drought. These are included in Table 6 (these are also listed among the definitions grouped in Tables 1, 2 and 4). Even among these papers, the rate of change differs by definition. Pendergrass et al. (2020) proposed a two-category change in two weeks, while Chen et al. (2019) also proposed a two-category change but over four weeks. Lorenz et al. (2018), through some experimentation, considered “rapid onset” to mean any change toward drought within 2, 4, or 6 weeks. Ford et al. (2015) looked for a three-category change toward drought in eight-week or less.

Not included in Table 6, but still notable, are Anderson et al. (2013) and Otkin et al. (2015b). Anderson et al. (2013) did not use the US Drought Monitor in their definition of flash drought but used the US Drought Monitor as a “standard of truth” as they compared hydrologic indicators during drought periods. Otkin et al. (2015b) did not use the USDM to define flash drought, but observed that "...according to the U.S. Drought Monitor (USDM), many locations across the central United States during the 2011 and 2012 flash droughts experienced up to a three-category increase in drought severity in only one month, meaning that areas that were drought free at the beginning of the month were characterized by severe to extreme drought conditions by the end of the month."

Table 6: Papers that use the US Drought Monitor to identify flash drought.

Reference	Specific criteria
Pendergrass et al. (2020)	**Flash drought definition 2** (application: US operations): two-category change in the USDM in 2 weeks, sustained for at least another 2 weeks
Chen et al. (2019)	"[W]e define a flash drought event as a drought event with greater than or equal to two categories degradation in a four-week period based on USDM."
Lorenz et al. (2018)	Generally: "if the USDM is more intense in [2, 4, or 6] weeks" then they considered this a rapid-onset to the drought situation.
Ford et al. (2015)	"We define a flash drought event in the US Drought Monitor record as three category or more increase in drought severity over 8 or less weeks."

Other Indicators Used

We have documented the types of indicators that have been used to define and measure flash drought (Table 7). Out of brevity, we have limited our list of indicators to only those used to define flash drought (i.e., not considering other drought analysis that may have been done in those papers or subsequent research that referenced those definitions, see Tables 2, 4 and 5). Soil moisture data is used in 11 definitions, evapotranspiration is used seven times, air temperature and precipitation are each used in six definitions, two definitions use an index for atmospheric evaporative demand (EDDI and ESR), satellite-based vegetation land-surface temperature and precipitation-evaporation-based drought indices (SPEI) are each used once (see Table 7).

Only one study used SPEI (Noguera et al. 2020) and none of the definitions below use the Standardized Precipitation Index (SPI) to define flash drought. Zhang et al. (2017) claim that these indices are not appropriate for flash drought measurement "due to the relatively untimely response to monthly input data versus immediate prevailing weather conditions" [note that Zhang et al. (2017) considered flash drought to be those that persist for a short duration—days to weeks]. Otkin et al. (2013) explains that precipitation-based drought indices, such as the SPI, can miss a flash drought because precipitation deficits are only one factor contributing to their development. Flash droughts can occur even when the SPI indicates only moderate precipitation deficits. Otkin et al. (2013) further explains that the Palmer Drought Severity Index (Palmer 1965) also may not be appropriate for flash drought detection. While it uses both precipitation and temperature observations, it is more effective at identifying long-term drought conditions developing over a period of several months and may be overly sensitive to temperature effects (Otkin et al. 2013). However, both the SPI and SPEI were used by Hunt et al. (2014) in their analysis of "rapid onset drought" which demonstrated that both the 1-month SPI and the 1-month SPEI were quite sensitive to the onset of the flash drought. Hunt et al. (2014) used the Svoboda et al. (2002) description as their definition of flash drought.

Table 7: List of indicator or indicator-types used in each flash drought definition.

Reference	Indicator Used
Noguera et al. (2020)	SPEI
Pendergrass et al. (2020)	EDDI US Drought Monitor
Li et al. (2020a)	Evapotranspiration
Li et al. (2020c)	Precipitation and Evapotranspiration
Liu et al. (2020a)	Soil moisture
Koster et al. (2019)	Soil moisture

Yuan et al. (2019)	Soil moisture
Zhang et al. (2019)	Precipitation
Christian et al. (2019b)	Standardized Evaporative Stress Ratio: ESR = ET/PET *ET and PET obtained from reanalysis data*
Wang and Yuan (2018)	Air temperature Evapotranspiration Soil moisture
Zhang et al. (2018)	Air temperature Evapotranspiration Soil moisture Precipitation
Park et al. (2018)	Three satellite-based drought indices use the combinations of the following data: ● Land surface temperature ● Normalized difference vegetation index ● Tropical Rainfall Measuring Mission precipitation ● Soil moisture
Yuan et al. (2018)	Air temperature Soil moisture
Ford and Labosier (2017)	Soil moisture
Zhang et al. (2017)	Air temperature Evapotranspiration Soil moisture Precipitation
Mo and Lettenmaier (2016)	Air temperature Evapotranspiration Precipitation
Mo and Lettenmaier (2015)	Air temperature Evapotranspiration Soil moisture
Anderson et al. (2013)	Soil moisture changes Evaporative Stress Index ($ESI=ET/F_{ref}$, where F_{ref} is a scaling flux)

There were a few studies that used indicators and indices to examine some characteristics of flash drought but did not use these as defining criteria nor categorical thresholds for flash drought identification. Most of the indicators used were also used by the papers listed in Table 7. A few other indicators, not listed above, include: crop condition data, cloud cover, 10-m wind speed, dewpoint depression (Otkin et al. 2013), a rapid change index for ESI, the SPI and total column soil moisture (Otkin et al. 2015a), a vegetative drought response index, dew point temperature (Otkin et al. 2016), a lower tropospheric Humidity Index, a convective triggering potential—similar to CAPE (Gerkin et al. 2018), various remote sensing techniques including NASA Soil Moisture Active Passive (SMAP) mission data and Satellite Solar-induced chlorophyll fluorescence (Yan et al. 2018; Kimball et al. 2019; and He et al. 2019). While not an exhaustive list, these papers demonstrate that flash drought can be looked at in a myriad of ways, using various indicators within the climate system, without necessarily setting terms or thresholds to diagnose a flash drought event (Zhang et al. 2020).

Summary

Since flash drought first appeared in the scientific literature in 2002 there have been 16 general descriptions and 19 papers providing defining criteria across 72 papers and 247 authors/co-authors. We

reviewed these definitions and grouped them by papers that provide only a general description, papers that define flash drought by the rate of onset or intensification, papers that consider flash droughts to be short-term drought events, and one paper that considers both rate of onset and short-term duration. We have also noted that the range of onset rates ranges from five days to eight weeks.

Based on how active the flash drought research field has become, we are motivated to convene a workshop on the topic to distill this available research among experts, find a consensus on general flash drought principles and/or definitions, and focus on future research and user needs. We have made these definitions available so that they can be discussed/debated in the upcoming flash drought workshop. A key objective of the workshop is to collectively produce a standard by which these definitions can be evaluated and applied to various user needs.

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