UNDERSTANDING FLASH DROUGHT DURATION, SPATIAL EXTENT, AND METEOROLOGICAL DRIVERS

by

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Drought is conventionally known as a slow-developing natural hazard. In recent years, a subset of drought events characterized by rapid onset has been identified and deemed “flash” droughts. These flash droughts can result in rapid soil drying and rapid vegetation degradation making them damaging to agriculture and the economy, so it is essential to develop reliable early warning systems for flash drought events. This study aims to compare the climatology between flash and non-flash droughts across the Contiguous United States (CONUS) and regionally to identify key differences in the drought types to improve early warning. Flash drought is defined as a two- or more category degradation in the U.S. Drought Monitor (USDM) in 4 weeks or less. Potential evapotranspiration (PET), vapor pressure deficit (VPD), maximum temperature (T_{max}), and minimum temperature (T_{min}) from the Gridded Surface Meteorological Dataset (gridMET) were also analyzed for flash and non-flash drought. It was found that using this definition of flash drought, flash droughts are up to 70% more likely to occur than non-flash droughts over all of the CONUS except the west coast. The South and Southwest regions are more likely to have more frequent and longer flash drought events than the Northwest and Plains regions. This study concludes that PET and VPD are the most reliable variables for differentiating between a flash and non-flash drought event. Furthermore, flash drought is most prevalent and will be the most difficult to predict in the South and Southwest regions and easier to predict in the Northwest and Plains. Also, using a flash drought definition of a drop in two or more categories in the USDM

may be too lenient. A narrower flash drought definition, such as a drop in two categories over a two- or three-week period, may be more reflective of the more damaging nature of flash drought events.

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CHAPTER 1

INTRODUCTION

Drought is a prolonged period of dryness usually caused by a precipitation deficit that leads to shortages in surface water and/or groundwater. Drought is one of the most damaging and expensive natural disasters globally due to its effect on agriculture and water resources as well as the large extent of the world that is vulnerable to drought. Extreme drought events can result in a variety of societal, agricultural, and environmental disruptions. The events can occur on multiple time scales (weeks to decades) and have many diverse impacts, resulting in difficultly creating a single definition that encompasses all possible impacts and regional variations.

Based on their impacts, droughts have been categorized as one of five types: meteorological, hydrological, socioeconomic, agricultural, and ecological (Otkin et al. 2018). Meteorological drought is a long-term precipitation deficit, hydrological drought focuses on water resources and impacts on streamflow and groundwater availability, agricultural drought refers to crop stress due to soil moisture loss, socioeconomic drought relates to the negative impacts on societal needs relating to economic goods and services affected by drought, and ecological drought is a lack of water resources that puts the ecosystem past a threshold of vulnerability. A drought event typically begins as a meteorological drought, and as favorable conditions for drought persist, it can evolve into hydrological drought and agricultural drought, with the socio-economic effects worsening as the drought continues.

In recent years, hydroclimatologists have recognized a subset of drought events that undergo rapid intensification and/or onset. Discussion of these rapid onset droughts began in 2002 when they were coined “flash droughts” (Svoboda *et al.* 2002); however, this term gained popularity particularly after the 2011 and 2012 droughts that impacted much of the United

States. Rapid onset or "flash" drought events are particularly damaging because they reduce the time available for drought impact mitigation, and therefore increase overall vulnerability. For example, the 2011 drought over the South-central U.S. caused an estimate of $7.62 billion in agricultural losses and $800 million in timber resources in Texas alone (Hoerling et al. 2013) while overall economic damage in the U.S. exceeding $35 billion (Otkin et al. 2015a). The dramatic, adverse impacts of flash drought necessitate accurate, timely monitoring and early warning systems to give stakeholders as much time as possible for impact mitigation. A better fundamental understanding of flash drought and its drivers is also necessary to reduce vulnerability to future flash drought events by adapting agricultural, industrial, and environmental systems.

The most recent literature regarding flash drought is focused on analyzing different definitions of flash drought (Osman et al. 2021; Lisonbee et al. 2021), analyzing different meteorological drivers of flash drought (Noguera et al. 2021; Parker et al. 2021), and possible early warning signs of flash drought (Chen et al. 2021), and the representation of flash drought in climate models (Hoffmann et al. 2021). Despite recent interest in flash drought-related research and media attention related to flash drought and its impacts, basic characteristics of flash drought such as the duration and spatial extent have only been explored recently (Osman et al. 2021). Lacking from this analysis is a comparison directly between flash droughts and non-flash droughts in the context of duration, spatial extent, and meteorological drivers. A better understanding of spatio-temporal flash drought characteristics, and especially the comparison between the two drought event types, will ultimately assist in drought early warning and reduction of related losses.

To contribute to the growing body of literature on flash drought, the research presented in this thesis is aimed at answering three primary research questions:

1. How does intensification rate affect duration and frequency of drought events?
2. What meteorological conditions are associated with differences in drought intensification rate?
3. How do differences in drought intensification rate vary by region?

To answer the first research question, the U.S. Drought Monitor (USDM) is used to differentiate flash and non-flash drought via the rate of intensification. The characteristics of the two event classifications are analyzed for the contiguous United States (CONUS) in section 4.2.1, and by region in section 4.2.2.

To answer the second research question, meteorological variables known to be important to drought formation are obtained from the Gridded Surface Meteorological Dataset (gridMET; Abatzoglou 2013). The meteorological variables: potential evapotranspiration (PET), vapor pressure deficit (VPD), minimum temperature (T_{min}), and maximum temperature (T_{max}) are analyzed for flash drought, non-flash drought, and non-drought events.

CHAPTER 2

LITERATURE REVIEW

In this chapter, the history of flash drought research will be presented. Examining drought intensification rates is a fairly new topic in the realm of hydroclimatology. In the last two decades, flash drought research has been focused on classifying the phenomenon with different datasets (section 2.2) and different definitions (section 2.3) as well as determining the meteorological drivers (section 2.4) and evolution (section 2.5) of these damaging natural disasters. Some research has also been done on the locality and timescale of these flash drought events (section 2.1). Lastly, from looking at the current state of flash drought research, areas of interest or gaps that need to be explored will be presented (2.6).

2.1 Region and timescale

Conventional slowly developing droughts can occur year-round and are caused by a long-term precipitation deficit and often above-average temperatures. Unlike these conventional drought events, flash droughts usually only occur in the warm season (during the spring, fall, and summer months) when the likelihood of high atmospheric water demand increases and mostly over the central United States (Chen et al. 2019). The most intense flash droughts in the United States occur over the Central Great Plains, Corn Belt, and western Great Lakes region (Chen et al. 2019, Christian et al. 2019). Slower-developing droughts occur nearly everywhere and have been getting shorter and less frequent. The exception to this is in the West, where drought is becoming more prolonged due to an ongoing precipitation deficit (Andreadis & Lettenmaier 2006). There is an extended slow-developing drought in the West that may be the worst it has been in 1200 years. The 2012-2014 drought event was found to be a 10,000-year drought event for the reference period from 1985-2014 (Robeson 2015).

2.2 Meteorological drivers of flash drought

Before discussing the methods of defining and predicting flash drought, it is important to understand the meteorological conditions that drive certain droughts to intensify more rapidly than others. Below normal precipitation and above normal temperature have been shown to be significant drivers of drought, but precipitation and temperature anomalies alone are ineffective in predicting flash drought because those factors alone are not enough to cause the rapid drying of the soil. Instead, when precipitation and temperature anomalies are coupled with an increase in evaporative demand – encouraged by lack of cloud cover, high radiative energy, high winds, and low humidity – it has been found to deplete soil moisture quicker and more effectively (Ford & Labosier 2017). The combination of evaporative demand, temperature, and precipitation anomalies over several days can lead to a shift from energy limited evapotranspiration (ET) to water-limited ET, resulting in wilting vegetation (Otkin et al. 2018). If conditions are correct, soil moisture depletion can occur very quickly in a matter of days, severely damaging vegetation. Other contributors are upper atmosphere ridging leading to surface high pressure that is commonly associated with decreased precipitation and humidity, increased solar radiation, and elevated temperatures (Ford & Labosier 2017). There has been some disagreement with the role of ET in flash droughts. Koster et al. (2019), with the use of MERRA-2 reanalysis data, suggested that while ET is important for the first few days of flash drought onset, but the overall contribution of ET to flash drought events is rather small compared to the relative contribution of precipitation deficits. This may be a result of ET typically having the largest decline rate during the fastest intensification period of drought (Chen et al. 2019). However, the consensus seems to be that a precipitation deficit is a requirement for drought, but the rate of intensification and its severity are influenced by other anomalies, such as ET (Otkin et al. 2018).

Land-atmospheric feedbacks were also found to play a role in the intensification of drought. A long-term precipitation deficit leads to desiccation of the soil, which can enhance heating and drying of the near-surface temperature, leading to high vapor pressure deficit. Furthermore, the decreasing soil moisture further perpetuates the negative precipitation anomalies as it limits evaporation from the soil and breaks the hydrological cycle (Miralles et al. 2019).

Recently, connections between flash drought and El Nino-Southern Oscillation (ENSO) were explored. Chen et al. (2019) found that out of five case study flash drought events they chose (2000, 2003, 2006, 2007, and 2012) four of the five events occurred either during or soon after a La Nina event. They attribute this teleconnection to the warmer and drier than normal conditions across the South that occur in the winter months because of warmer Pacific Ocean temperatures during La Nina years. The warmer and drier conditions make flash drought development more likely due to the increased atmospheric moisture demand that can arise with La Nina influence. ENSO is not a popular subtopic in flash drought literature, so the knowledge is limited in this area. This may change once a better general climatology of flash drought is developed.

2.3 Flash Drought Variables, Indices, and Datasets

The realm of flash drought research is very diverse. There are many ways that flash drought has been defined using drought monitors, indices, and other stand-alone meteorological variables. The common monitors, indices, and variables used to define and predict flash drought will be presented in this section. The next section (2.3) will explore the specific definitions created with the monitors and indices presented in this section. There are also a variety of variables and indices used to predict a flash drought often following the specified flash drought definition.

2.3.1 Flash Drought Variables

Generally, it has been determined that a precipitation deficit and above average temperatures often precede a drought event. However, the most rapidly intensifying drought events are followed by an increase in evapotranspiration caused by a decrease in humidity. As a result, the most common variables used for defining, analyzing, and predicting flash drought events are evapotranspiration or potential-evapotranspiration, air temperature, precipitation, and soil moisture (Lisonbee et al. 2021). However, while these variables are sometimes used on their own, they are often integrated into different indices and monitors which are then used in flash drought studies.

2.3.2 U.S. Drought Monitor (USDM)

The U.S Drought Monitor (USDM) is used in this study to define flash drought, however, there are many other ways of defining and analyzing flash drought. Highlighting the USDM first in this section will aid in giving context to the effectiveness of other variables and indices later in section 2.3.

It is important to utilize publicly available drought monitors when researching flash drought to bridge the gap between the scientific community and stakeholders negatively affected by drought. Effective communication between these two groups is essential to minimize the potential economic and environmental damage that can be caused by drought events. Drought monitors are also usually a synthesis of various variables or other indices that are important to drought formation, making them a well-rounded and overarching representation of drought conditions for public and scientific communities. As a result, these monitors can be extremely useful in flash drought research.

Following the droughts of 2011 and 2012, the ability of commonly used drought monitors to identify rapid onset drought in a timely matter was of the utmost importance and was the first step of flash drought research. The first publicly available drought monitor/index used to define flash drought was the U.S. Drought Monitor (Ford et al. 2015). The USDM integrates information from various variables and indices which are analyzed by local/regional climatologists and hydrologists from all over the country to produce a map weekly describing the spatial extent and severity of drought. The severity of drought in the USDM is classified into 5 categories from "abnormally dry” to “exceptional drought” (Svoboda et al. 2002).

The USDM deserves a dedicated section in this literature review because it is unique in the realm of flash drought research. The USDM has been used extensively as a baseline to compare the flash drought early warning effectiveness of other variables and indices (Otkin et al. 2013, Otkin et al. 2015a, Otkin et al. 2016, Lorenz et al. 2017, Christian et al. 2019). It is also commonly used to define flash drought (Ford et al. 2015, Chen et al. 2019, Pendergrass et al. 2020) In this study, the USDM will be used to define flash drought and act as a baseline to analyze the early warning effectiveness of other meteorological variables. The USDM is one of the best tools in drought monitoring because of its expert synthesis of multiple variables and it is a monitor commonly used by flash drought stakeholders. The USDM will be used to develop a flash and non-flash drought climatology to answer the first research question. The USDM will also be used to answer research questions two and three by examining the lead time of certain meteorological variables of flash and non-flash drought to the USDM in regions where both drought types are prominent. The purpose of this is to highlight the variables that are anomalous weeks before a flash drought is detected by the USDM.

2.3.3 Flash Drought Indices

There have been many indices created and utilized since the term flash drought became popular. The goal of these indices was to combine multiple meteorological drivers of flash drought and/or statistically manipulate the variables to determine the rate of change, percentiles, anomalies, and other features within the variables to better identify and predict flash drought events. The indices commonly used in flash drought studies are the evaporative stress index (ESI; Anderson et al. 2013, Otkin et al. 2013, Otkin et al. 2016), the Standardized Evaporative Stress Ratio (SESR; Christian et al. 2019), the Standardized Potential-Evapotranspiration Index (SPEI; Hunt et al. 2014, Noguera et al. 2020), the Evaporative Demand Drought Index (EDDI; Pendergrass et al. 2020, Parker et al. 2021), and the Vegetation Drought Response Index (VegDRI; Otkin et al. 2016)

The Evaporative Stress Index (ESI) used standardized anomalies from ET/ ET flux, based on the Penmen-Monteith formula (Allen et al. 1998) as quantified by the land surface temperature based Atmospheric Land Exchange Inverse (ALEXI; Anderson et al. 2007). It was used to remove the ET variables that are not moisture related, like solar radiation (Otkin et al. 2015a). When soil moisture in the ESI was compared to the USDM, it was found that large negative anomalies either coincide or lead the USDM drought detection by several weeks (Otkin et al. 2013). The ESI was useful as an early warning drought metric because it depicts vegetation health, which can be very useful to the stakeholders mentioned earlier compared to indices that rely on soil moisture alone.

Two indices utilize ESI: the Rapid Change Index (RCI) and the Standardized Evaporative Stress Ratio (SESR). Otkin et al. (2013) introduced RCI as a way of monitoring the change in ESI over time. This index is a cumulative magnitude of weekly ESI change anomalies during rapid change events (Otkin et al. 2015b). The SESR uses the same calculation as ESI (ET/PET), but it was standardized so it can be used over multiple time scales, as a comparison between different regions, and a comparison between different seasons (Christian et al. 2019).

The indices mentioned so far are satisfactory for up-to-date information about current vegetation and soil moisture stress, but another important component to monitoring vegetation stress is the change in stress over time. Two main advantages of the Evaporative Demand Drought Index (EDDI) are that similar to ESI, it is independent of precipitation, but it can be used to distinguish between the role that individual drivers have on drought onset and persistence (McEvoy et al. 2016). The EDDI contains a multi-scalar component, which is important to combat the lack of analyses based on change over different time periods (Hobbins et al., 2016). It can be used by stakeholders to look at variation data from one week up to one year. EDDI measures the signal of drought through the response of evaporative demand to surface drying anomalies from a relationship between evaporative demand and ET that develops under moisture limitations at the land surface leading to decreased ET and increased evaporative demand (Hobbins et al. 2016). That being said, it was argued that EDDI is not a good index for flash drought research because the independence and separation of the variables take away from the full picture of flash drought. Flash drought requires a complete combination of all factors (precipitation, soil moisture, temperature, vapor pressure deficit, wind speed, evapotranspiration, etc.) to be fully evaluated (Otkin et al. 2018).

Similar to ESI, it was also found that North American Land Data Assimilation System (NLDAS) soil moisture models lead the report of drought from the USDM by up to 6 weeks depending on the region (Otkin et al. 2015a). The NLDAS models use remotely sensed data to calculate soil moisture at different soil depths using energy and water balance equations. The models use varying soil and vegetation data based on region, so taking the mean of all the models, can be a solution to the problems that can occur with different soil and vegetation characteristics**.** Since soil moisture is directly related to evaporative demand and evapotranspiration, using an index based on soil moisture is an important indicator for flash drought identification.

A more direct measurement, but an expensive and limited dataset, *in situ* soil moisture data, like the extensive Mesonet dataset available in Oklahoma, also showed a 2–3 week lead time improvement in soil moisture percentiles over the USDM (Ford et al. 2015). In situ soil moisture data has been shown to be useful in predicting a flash drought event; however, in situ sites are far and few between. Oklahoma was one of the few states that had enough soil moisture stations to be useful for flash drought research, as erecting more stations is too expensive and unreasonable considering the other indices available. While other indices may not be as exact, the cost-benefit analysis favors satellite data and calculations to monitor and predict flash drought rather than the widespread deployment of new instruments.

2.4 Definitions

There is a lack of a consensus about the definition of flash drought despite numerous recent publications on the subject (Wang and Yuan 2018; Chen et al. 2019; Noguera et al. 2020) Flash drought has at least 49 definitions or descriptions published since 2002, although some of them are extremely similar (Lisonbee et al. 2021). There are two schools of thought: flash drought should be defined by the rapid intensification of the event, or it should be defined by the short life span coupled with the high severity of the event.

2.4.1 Short Duration Flash Drought

Senay et al. (2008) described flash drought as a “short term, yet severe event” as a result of precipitation deficits and high temperatures. Hunt et al. (2009, 2014) referred to flash drought as a short-term event although acknowledged the often rapid onset of these events. Other publications have described flash drought as an event lasting the length of a season (Obringer et al. 2016), a rapid onset drought that lasts two to four months depending on location (Gerken et al. 2018), short-term events with rapid on-set (Jin et al. 2019), an episode with sudden onset and a short duration (Stojanovic et al. 2020), or a sharp intensification of lower intensity droughts that last days or weeks (Trnka et al. 2020). Mo and Lettenmaier (2015, 2016) suggest that there are two types of flash drought: heatwave flash drought and precipitation deficit flash drought. As the name suggests, precipitation deficit flash drought results from a lack of precipitation which results in a decrease in ET and an increase in temperature (Mo and Lettenmaier 2016). Heatwave flash droughts result from an increase in temperature which causes ET to increase which leads to a decrease in soil moisture (Mo and Lettenmaier 2015). Their suggested definition for flash drought in both cases is based on duration and mandates that soil moisture must be below the 40th percentile in a five-day period to be considered a flash drought. Zhang et al. (2017) used a similar method by defining a heatwave flash drought and a precipitation deficit flash drought as conditions under which the maximum temperature anomaly is greater than one standard deviation, the soil moisture drops below the 40th percentile, and the evapotranspiration anomaly is in the positive and negative phase, respectively. Wang et al. (2016) also use this definition of precipitation deficit flash drought when examining flash drought trends in China. Most of the definitions based on short term criteria are defined by an anomaly of a meteorological observation such as air temperature, soil moisture, or evapotranspiration meeting a certain standard deviation or precipitation being below a certain percentile (Mo and Lettenmaier 2015, 2016; Zhang et al. 2017; Yuan et al. 2018).

2.4.2 Intensification Rate Flash Drought

The first definition of flash drought was coined by Svoboda et al. (2002) and highlighted that a flash drought refers to a severe heatwave and high temperatures causing a rapid onset of drought that results in rapid crop deterioration, increased fire potential, and impacts to livestock health. This general description has been cited very broadly in the flash drought literature. Many papers adhere to the original definition of flash drought based on the rate of intensification. A definition based on intensification is argued to be more appropriate because a duration-based definition neglects the “flash” in flash drought: the rapid intensification of different magnitude over time (Otkin et al. 2018). A drought event that intensifies rapidly and then persists for weeks or months would result in similar, if not more, economic, and environmental damage compared to a rapidly intensifying event that recovers quickly. Regardless of if the drought persists after the rapid intensification, the rate of intensification is the most important and damaging variable when defining flash drought, thus the definition should reflect that.

The USDM has been often used to define flash drought. Otkin et al. (2018) suggest, for example, that a two-category increase in drought severity over a 6-week time period could be considered a moderate flash drought, whereas a four-category increase over the same period would be classified as an extreme flash drought. Even within the term of flash drought, there can be different levels of magnitude. More recently, Chen et al. (2019) defined flash drought as at least a two-category intensification in drought conditions over a four-week time frame as opposed to six weeks. And the most constraining definition has been a two-category change in the USDM in 2 weeks, sustained for at least another 2 weeks (Pendergrass et al. 2020)

Soil moisture is also a popular way of defining flash drought without short-duration criteria. All of the flash drought definitions that include a short-duration component cite the 40th percentile as being the beginning of a flash drought. However, the 40th percentile of soil moisture was not dry enough for substantial damage to occur (Otkin et al. 2018). The most recently suggested definition of flash drought is a change in soil moisture from above the 40th percentile to below the 20th percentile in 4 pentads or 20 days (Ford & Labosier 2017). The new definition requires soil moisture to drop below the 20th percentile, resulting in much drier and more harmful conditions than the previously suggested 40th percentile. The new definition also requires a severe rate of intensification in a relatively short period of time.

A rapid decrease in soil moisture was one of the first indicators of a flash drought and seeing that evaporative demand is directly linked to soil moisture depletion, Otkin et al. (2016) suggested that the definition be derived from the North American Land Assimilation System (NLDAS) soil moisture data, making NLDAS the standard for flash drought research. This does not minimize the utility of other indices for use by stakeholders to manage their resources. In speaking with stakeholders, Otkin et al. (2015b) concluded that ESI is the favored index for their uses with a rating of 89%, although the study did not include NLDAS data in the poll. ESI was found to be an accurate predictor of the USDM 2-6 weeks before a flash drought event, meaning that using the ESI and/or NLDAS to predict flash drought based on a definition using the USDM may be useful.

Inconsistencies within the flash drought lexicon have led to there being many different methods of defining and analyzing flash drought. Diversity is not necessarily a negative. It can promote examining rapidly intensifying drought impacts from multiple angles, which is important due to the variety of stakeholders drought can impact. However, due to the current state of flash drought research, caution must be taken in generalizing temporal trends and hot spots (Osman et al. 2021).

2.5 Drought Evolution

All drought events will vary in terms of intensification rate and severity due to variations in antecedent conditions and atmospheric anomalies. It has been shown that drought events require high temperature and low precipitation, but what separates rapid onset drought events from slower developing drought events is the atmospheric water demand, potential-evapotranspiration (PET), and the difference between precipitation and potential-evapotranspiration (P-PET; Ford & Labosier 2017). Examining the difference between precipitation and PET is important to ensure that increases in atmospheric demand are not compensated for by precipitation events. Datasets such as the SPEI (as discussed in section 2.3.2) are ideal for this purpose.

Determining the causes of increased potential-evapotranspiration is important to understand how a flash drought evolves. During the onset phase of flash drought, the top 5 centimeters of soil will experience a soil moisture deficit and then the soil moisture deficit will move farther down into the soil moisture column (Otkin et al. 2016). The type of plant and the rate of evapotranspiration can affect the rate at which this happens. Shallow-rooted vegetation will remove moisture from the soil only as deep as the roots can reach. Deep-rooted vegetation can exacerbate the evolution of flash drought by decreasing the soil moisture faster farther down in the soil column (Oktin et al. 2018). This is the reason that it has been important to monitor soil moisture in the entire soil column as well as why ET and PET are driving factors in determining if a flash drought will occur.

As vegetation depletes the available soil moisture as far as down as the roots can reach into the soil column, visible signs of drought begin to occur such as the yellowing or curling of leaves. During flash drought events in which this can happen very quickly, and the extreme dryness can then last several weeks or more, all of the available soil moisture can be depleted. When this occurs, vegetation can experience temporary or permanent senescence leading to the further perpetuation of drought through the decrease in evaporative cooling and thus elevated sensible heating (Otkin et al. 2016). Furthermore, droughts, in general, are becoming longer and more frequent which is decreasing the amount of time available for vegetation recovery. As a result, there is a higher risk for ecosystem damage and degradation of the land carbon sink (Schwalm et al. 2012). Since vegetation experiences more damage in a short amount of time from these flash drought events, vegetation damage may be exacerbated due to these rapid-onset events.

The word "flash" in the context of drought has also been used to describe the recovery of an event. Recovery of flash drought events was briefly touched upon by Otkin et al. (2019). They noted that the 2015 flash drought during the growing season ended due to precipitation events at the end of October of that year. The heavy rainfall across the region was a result of a stalled frontal boundary in the lower troposphere and tropical moisture from Hurricane Patricia. It took two weeks to recover from the drought event, and thus, they called this "flash recovery." A recent addition to the conversation of flash drought and drought in general, a flash recovery is when a single or several precipitation events occur in a short time period enough to the point where the soil moisture is replenished, and vegetation is no longer in a state of water-limited evapotranspiration. The rapid recovery of flash drought events is heavily dependent on the amount of damage the drought conditions caused the vegetation. If the vegetation is too damaged or dormant, it will take much longer to recover from the agricultural drought (Otkin et al., 2016). Flash recovery is not related to flash drought and is a different area of study mostly analyzing how large a precipitation event would have to be in order to end a drought of different severities with one precipitation event. Nonetheless, it is important to note as the use of the word “flash” in the drought lexicon is still in the beginning stages of development and there is a lack of a definitive consensus on the use of the term.

2.6 Summary

Flash drought and drought intensification rate research has focused on meteorological drivers of flash drought, the examination, and creation of different datasets aimed at better identifying the key factors of flash drought, and the evolution of flash drought. There has been a lack of consensus on an objective definition of flash drought. The connection between soil moisture anomalies and evaporative demand has been examined, but the comparison of these meteorological events between flash and non-flash droughts has not been explored. More research is necessary to compare conditions associated with flash drought and slowly developing drought to determine if any significant differences can be distinguished. There has been a lack of research on the comparison between flash and non-flash drought climatology. As discussed in section 2.3, the definition of flash drought is somewhat subjective. Furthermore, the characteristics of flash droughts such as the extent, duration, and severity and if or how those characteristics are at all affected by the intensification rate of drought have yet to be explored. These knowledge gaps preclude accurate early warning of flash drought and mitigation of the negative environmental, societal, and economic effects of flash drought. Furthering flash drought research is imperative to support the stakeholders negatively affected, especially in a changing climate.

The overarching theme from the literature is a lack of consistency between flash drought definitions and the indicators used to create the definitions. Only one thing is agreed upon across nearly all of flash drought literature which is that flash drought is different and more serious than slower developing droughts and that this severity is caused by some combination of a precipitation deficit, high temperatures, and high atmospheric demand caused by some combination of low humidity, high evapotranspiration, high wind speeds, high solar radiation, or upper atmosphere ridging.

CHAPTER 3

DATA AND METHODOLOGY

3.1 Introduction

This chapter describes the datasets used in this research and details regarding the methods applied to the datasets to meet the stated research objectives. Two primary data sources were used. First, the U.S. Drought Monitor (USDM) drought severity data were used to define, identify, and analyze the spatial and temporal characteristics of flash drought and non-flash drought. Second, daily surface meteorological data from the Gridded Surface Meteorological Dataset (gridMET; Abatzoglou 2013) was used to create anomalies for potential evapotranspiration (PET), vapor pressure deficit (VPD), minimum daily temperature (T_{min}), and maximum daily temperature (T_{max}) and the distribution and trends of those anomalies for one to six weeks out from a flash, non-flash, or no drought week (according to the USDM).

3.2 Data

3.2.1 U.S. Drought Monitor Drought (USDM) Intensity Data

The U.S. Drought Monitor (Svoboda et al. 2002) is used to define and characterize flash and non-flash drought events. Based on existing literature, the most common indicators used to define flash drought have been ET, soil moisture, temperature, and precipitation (Lisonbee et al. 2021). The USDM is a straightforward classification system for drought that compiles expert synthesis of various data sources including the Palmer Drought Severity Index (PDSI) (Palmer 1965), CPC Soil Moisture Model Percentiles (CPC/SM; Huang et al. 1996), U.S. Geological Survey (USGS) Daily Streamflow Percentiles, Percent Normal Precipitation (Willeke et al. 1994), Standardized Precipitation Index (SPI; McKee et al. 1993), and remotely sensed Satellite Vegetation Health Index (VT; Kogan 1995). The lead responsibility for synthesizing the data and preparing the Drought Monitor rotates among several authors from the National Climatic Data Center (NCDC), the National Drought Mitigation Center (NDMC), the Climate Prediction Center (CPC), and the United States Department of Agriculture (USDA) who take shifts as the product's lead author. The result is a weekly map of the contiguous United States (CONUS) as well as Alaska, Hawaii, and Puerto Rico that is valid Wednesday through Tuesday at 12 PM UTC and released every Thursday morning. An example of this map is shown in Figure 1. The drought severity maps are available in a shapefile format created in ArcMap. Drought conditions are represented by five categories D1 (moderate), D2 (severe), D3 (extreme), D4 (exceptional), and an additional category, D0, that represents areas with abnormally dry conditions that may precede drought conditions.

This study uses the USDM drought severity data valid every Tuesday from 2000 to 2019 (1044 maps in total). To use USDM data for numerical analysis, the data was rasterized into gridded outputs that are 1/24th degree spatial resolution covering the CONUS to match the spatial resolution of gridMET meteorological data. Each grid point was assigned a numerical value of 0, 1, 2, 3, or 4 to represent the USDM categories D0, D1, D2, D3, and D4 relatively. Areas of no drought were assigned a value of -1.

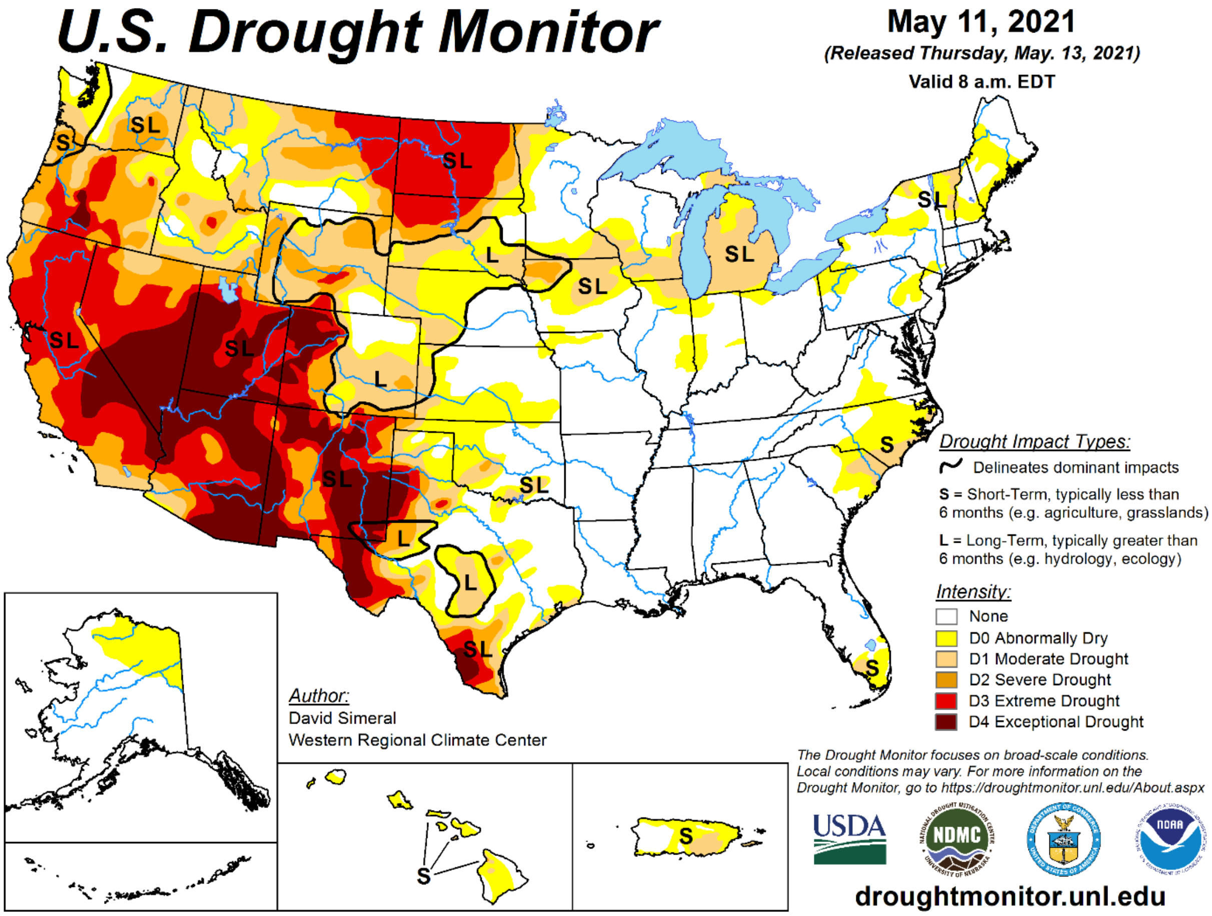


Figure 1. An example of the USDM map released every Thursday. Shown is the map valid May 11, 2021, and released May 13, 2021.

3.2.2 Gridded Surface Meteorological Dataset (gridMET) Meteorological Data

The meteorological data for this study will be obtained from gridMET (Abatzoglou 2013). The dataset provides daily surface meteorological data for the contiguous U.S. at 4 km or 1/24th degree spatial resolution. The climate data is a blend of spatial attributes from PRISM and temporal attributes from NLDAS-2 using climatically aided interpolation (Abatzoglou 2013). Some variables that are available from gridMET are maximum temperature, minimum temperature, precipitation accumulation, downward surface shortwave radiation, wind velocity, maximum relative humidity, minimum relative humidity, and specific humidity. gridMET also includes some derived variables such as reference evapotranspiration (ASCE Penman-Monteith), and mean vapor pressure deficit. This study will use daily maximum temperature (T_{max}), minimum temperature (T_{min}), potential evapotranspiration (PET), and mean vapor pressure deficit (VPD) from 1979 to 2019. The main driving force behind drought is precipitation deficit, and the USDM is based heavily on SPI data, so including precipitation from gridMET was not necessary. While precipitation deficit is required for drought formation, its presence alone is not enough for rapidly intensifying droughts. The most rapid intensification of droughts has been associated with a lack of clouds, positive temperatures, high winds, and dew point depression (Otkin et al. 2013). Reference evapotranspiration and mean vapor pressure deficit were chosen for this study because they would both contain signals from low clouds, high winds, and humidity (dew point depression).

3.3 Flash Drought and Non-Flash Drought Event Classification

Weekly drought magnitude data for 2000-2019 was retrieved from the USDM, regridded to 1/24th degree spatial resolution, and labeled 0 through 4 corresponding to the USDM categories as well as -1 for areas of no drought. The weeks in categories 1, 2, 3, and 4 were considered to be drought (i.e., excluding the "abnormally dry" and non-drought categories). Each drought event was defined as a period of weeks beginning with 4 consecutive weeks of drought conditions and terminated by 4 weeks of non-drought conditions. During this time, the drought event may decrease in intensity to the point where drought is no longer present, but if the event returns to drought conditions in 4 or fewer weeks, the drought event continues. The drought events were then further split into flash events and non-flash events. A flash drought event was defined as a worsening of two or more categories over a 4-week period either at the beginning or within a drought event. A non-flash drought event was any drought event that did not meet the criteria for a flash drought event. Based on the flash drought event and non-flash drought event classification, several climatological drought characteristics of interest were calculated and analyzed such as the number of events that occurred during the length of the dataset, the total length of weeks in each drought event type over the length of the dataset, and the mean and median length of the two drought event types per grid point.

3.4 Establishing a Flash Drought Climatology

In order to establish a flash drought climatology, the spatial characteristics of flash drought were analyzed. The first research objective of this study was to examine the ways that drought intensification rate affects the duration, and the flash drought climatology includes an analysis of the length of flash or non-flash drought events (in weeks) and the number of flash or non-flash drought events by grid cell from 2000-2019.

The main focus of spatial drought characteristics was the length of the drought events and the number of drought events experienced per grid cell over 2000-2019 to answer the research question regarding the differences in duration and extent between flash and non-flash drought. The first part of the USDM characteristics results section provides visual representations of some variations of these characteristics for all of the CONUS. The results are separated by event: non-flash drought, flash drought, and all drought events (a combination of flash and non-flash drought events). The second part of the USDM characteristics results section breaks down the differences by region.

3.5 Regional Analysis

Drought conditions vary by region. Flash drought has been found to occur mostly in the central U.S., while non-flash drought can occur everywhere in the U.S. (Chen et al. 2019). It has also been found that the upper Midwest and southeast regions have a higher frequency of flash drought occurrence with early-season flash droughts seen in the Northeast and late-season flash droughts also seen in the Great Plains (Ford and Labosier 2017). Flash drought and non-flash drought characteristics were separated by region to determine if any regional differences exist between the event types. Determining regional differences is necessary to understanding where flash drought and/or non-flash drought events are the most prevalent. This information helps concentrate analysis to the regions most relevant to the research questions. Differentiating between flash and non-flash drought and between regions helps to better understand the spatial differences between the two drought types. The contiguous United States was split up into 7 regions: Northwest, West, Plains, Southwest, Midwest, South, and Northeast (Figure 2). These regions are roughly based on the regions used by the USDM.

To ensure an adequate sample size for analysis, only grid cells with five or more flash drought events and five or more non-flash drought events were used in the analysis. The grid cells that meet the criteria are shown in Figure 3. In addition, only regions that had 10% or more grid cells meeting the criteria were considered for analysis. Those regions are the Northwest, Plains, Southwest, and South. The number of total grid cells, the number of grid cells that have five or more of both flash and non-flash drought events, and the percent of grid cells that meet the criteria are listed in Table 1.

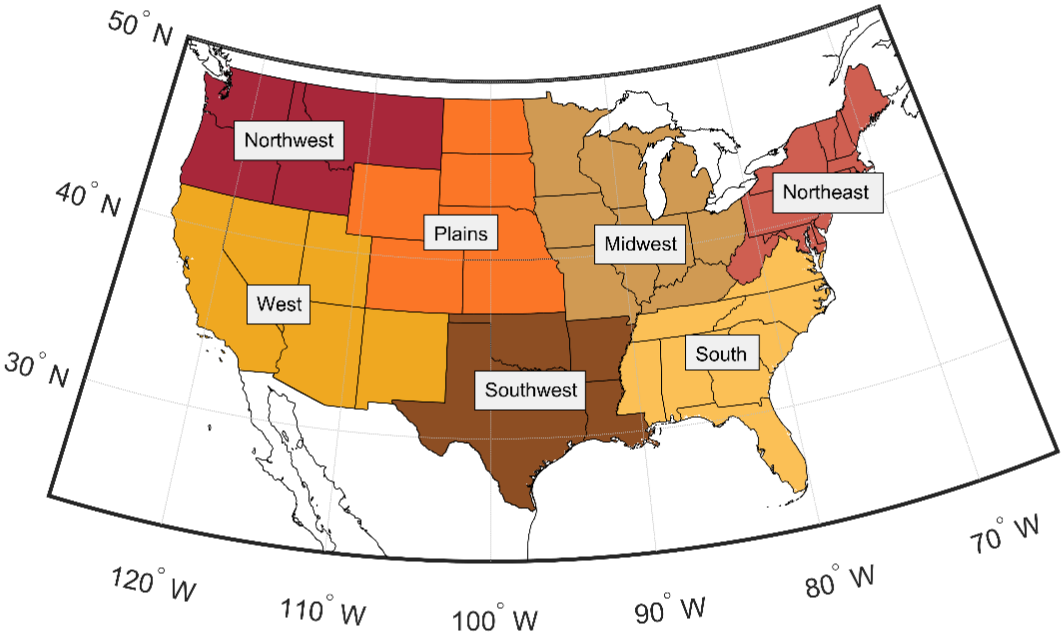


Figure 2. The 7 regions of the contiguous United States used for drought analysis.

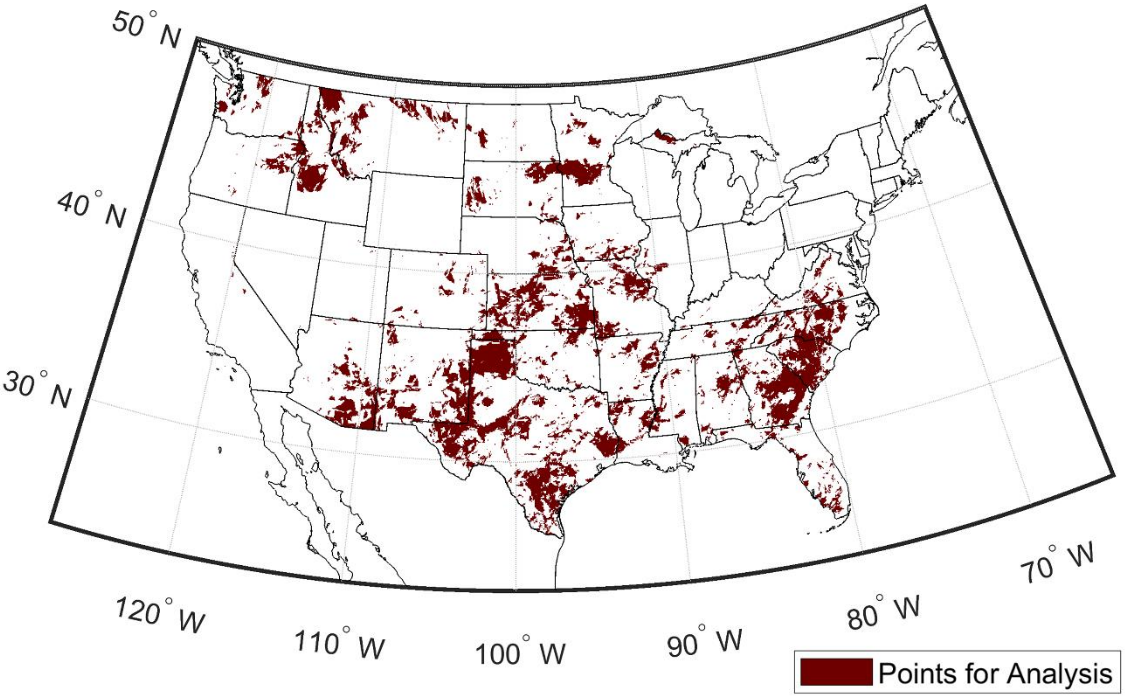


Figure 3. The grid points that meet the criteria for the adequate sample size for analysis of having 5 or more of both non-flash and flash drought events occur between 2000-2019.

Table 1. Number of grid points in each region, number of grid points that meet the criteria of having 5 flash drought and 5 non-flash drought events based on the USDM drought severity data, 2000-2019, and percent of grid points that meet the criteria. Regions that have more than 10% of grid points that meet criteria are highlighted in gray.

Region	Grid points (total)	Grid points (for drought analysis)	Percentage of total grid points used for analysis
Northwest	68,310	8,391	12.3
West	88,990	6,824	7.7
Plains	82,885	9,070	10.9
Southwest	62,383	16,514	26.5
Midwest	90,866	6,151	6.8
South	54,718	13,311	24.3
Northeast	33,668	2	0

3.5.1 Kernel Smoothing Density Distribution

A kernel distribution was used to represent the distribution of the flash drought and non-flash drought characteristics by grid cell in each region. A kernel distribution is a nonparametric representation of the probability density function (pdf) of a random variable. The "smoothing" part of the kernel smoothing density distribution refers to a smoothing function that is used to smooth the resulting density curve using a specified bandwidth. For any real values of x, the kernel density estimator's formula is given by:

$$\hat{f}_h(x) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x-x_i}{h}\right),$$

Where $x_1, x_{2,\ldots,}x_n$ are random samples from an unknown distribution, n is the sample size, K is the kernel smoothing function, and h is the bandwidth.

3.6 Analysis of Regional Climatology using gridMET

For the analysis of the regional climatology, potential evapotranspiration (PET), vapor pressure deficit (VPD), maximum temperature (T_{max}), and minimum temperature (T_{min}) will be used. Anomalies for potential PET, VPD, T_{min}, and T_{max} were calculated by finding the mean per moving seven-day window from March to October for 1979-2019 and finding the deficit between the mean for each moving seven-day period over 41 years and the seven-day mean for each year for the USDM data set (2000-2019). The anomalies were then compared to flash and non-flash events. The one-week anomalies were recorded for one through six weeks out from the beginning of a drought event and no drought event.

The beginning of a non-flash drought event was defined as the first Tuesday in which a drought event begins, and the beginning of a flash event is defined as the first Tuesday in a drought event that the drought intensifies two or more categories in four weeks whether that is the first week of the event, or if that occurs during the middle of the event. A no drought event is any Tuesday that is not within a drought event. The anomaly calculations were used to examine the distribution and trends of the meteorological variables for one to six weeks out from an event for each of the four chosen regions.

3.7 Two-Sample T-Test

To analyze the difference in means of the meteorological variables used for flash and non-flash drought regional analysis, two-sample t-tests will be used. The objective of this test is to determine if two means are significantly different with the null hypothesis being that the difference between the two means is zero. A Bonferroni correction is necessary because there are many t-tests conducted which significantly raises the possibility of a Type-I error. The Bonferroni correction reduces the probability of a type-I error by dividing the number of tests by alpha. For this study, there are 288 tests and an original alpha value of 0.05 resulting in an alpha value of 0.00017.

CHAPTER 4

RESULTS

4.1 Introduction

This chapter is divided into two parts corresponding to the first two primary research questions in chapter 1; the first part establishes a flash drought and non-flash drought climatology using USDM for all of the CONUS and then split up by region. Part 2 focuses on relating meteorological data to flash and non-flash drought events at different lead times to explore the difference between the events in the context of antecedent conditions. The first part of this chapter will present the results of the flash drought and non-flash drought spatial characteristics from the USDM drought severity data for the CONUS as well as a regional analysis. Spatial characteristics of the CONUS include the number of occurrences per event type and the proportion of the number of each event type. It will also present the total amount of time spent in each drought type and the mean and median length of each event type per grid cell of the study area. including the number and length of events as well as a regional breakdown of the results. As described in Chapter 3, the regions used for analysis are the Northwest, Plains, Southwest, and South (Table 1). The regional results include the number, total length, and mean length to determine how the characteristics of flash drought and non-flash drought events vary from region to region.

The second part of this chapter will present the results from the meteorological data analysis using gridMET as it relates to flash and non-flash characteristics from the USDM. The meteorological variables used include potential evapotranspiration, vapor pressure deficit, maximum temperature, and minimum temperature. From these variables, 1- through 6-week anomalies were derived for flash drought, non-flash drought, and no drought events. They are visualized by region and by variable using boxplots and mean trend lines. The significance of means between each variable, lead time, and region will also be presented using two-way T-tests.

4.2 The USDM Flash Drought and Non-Flash Drought Characteristics

This section examines spatial characteristics of flash and non-flash drought first for the entirety of the CONUS, and then characteristics are compared between the regions that have the most prevalence of flash and non-flash drought events.

4.2.1 Drought in the Contiguous United States

Separating flash drought events and non-flash drought events allows the analysis of the spatial differences between the two event types in the context of the USDM. Characteristics such as the number and length of events across the CONUS will be presented in this section.

Most of the CONUS has experienced about 8 to 14 drought events over the 20 years from 2000 to 2019 (Figure 4). The South and Southwest have experienced relatively more drought events with areas in Texas and Georgia reaching up to 18 events in 20 years. The Northeast Region and the West, specifically California and Nevada, have experienced fewer drought events relatively. Parts of the Northeast have only encountered between one and six events. An area in northern West Virginia and Southwest Pennsylvania has only experienced none or one drought events. The Southwest and South have more flash events compared to the rest of the CONUS while the Northeast and West have few flash events. There is a notable hotspot of drought events in Texas, southern Oklahoma, Louisiana, and Arkansas, as well as another hotspot of increased frequency of drought events in Georgia and South Carolina. The number of non-flash events are relatively consistent across the CONUS with a sparse area in the Northeast consistent with the number of all drought events.

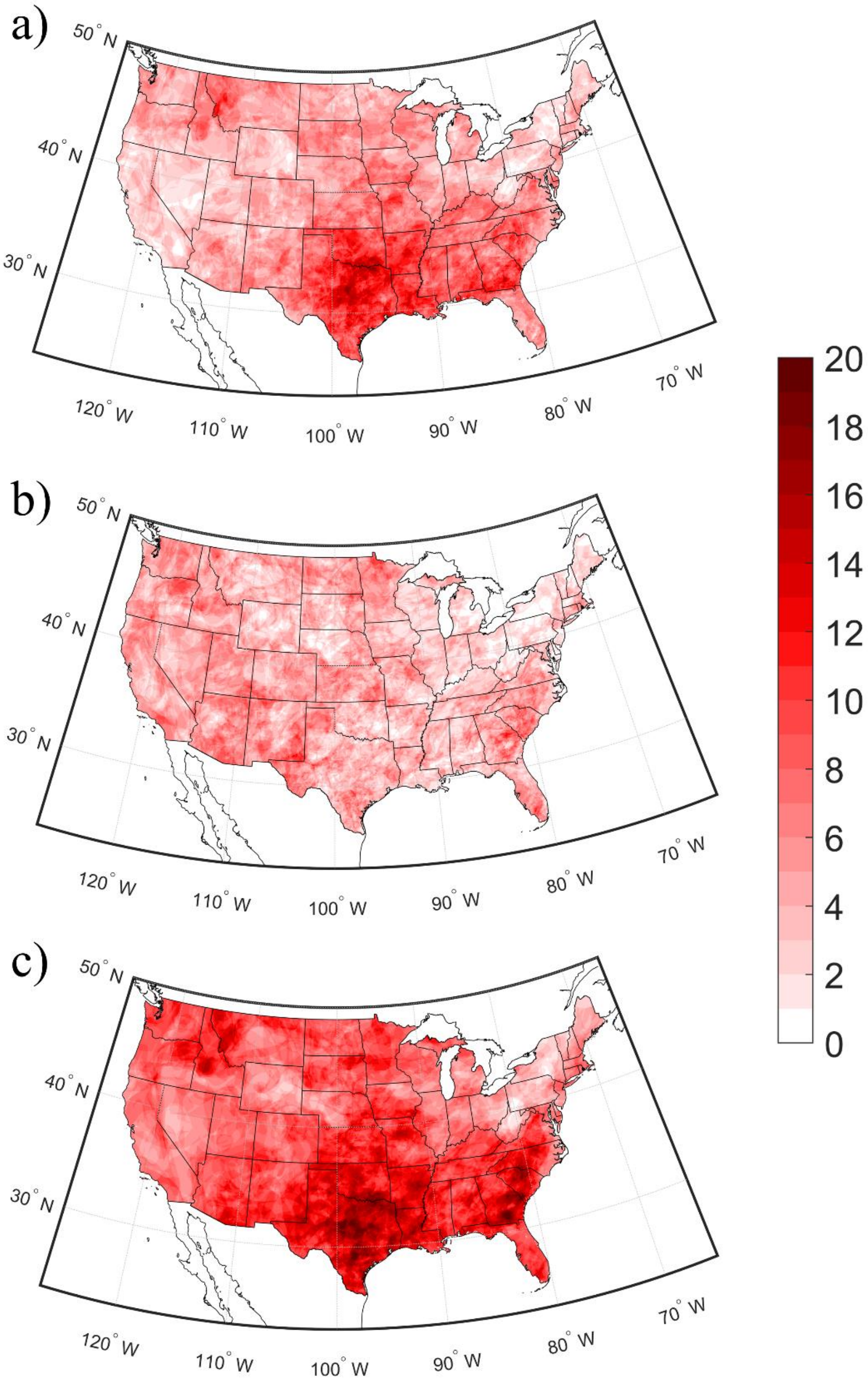


Figure 4. Number of drought events from weekly USDM drought severity data, 2000-2019. Results are shown a) flash drought events, b) non-flash drought events, c) all drought events.

Figure 5 shows the proportion of the number of a drought event type (flash and non-flash) to all drought events. Flash droughts are more common than non-flash droughts in the majority of the study region. In many grid cells in the South, Southwest, Midwest, and the Plains, fewer than 10% of all drought events have been non-flash droughts. In most of the CONUS, more than 70% of drought events are flash. Parts of the West and Northeast are the only areas that experience a larger proportion of non-flash drought than flash drought. These areas include southern Oregon, northern and southwestern California, mid- and Southwest Nevada, northern Arizona, and southern Colorado.

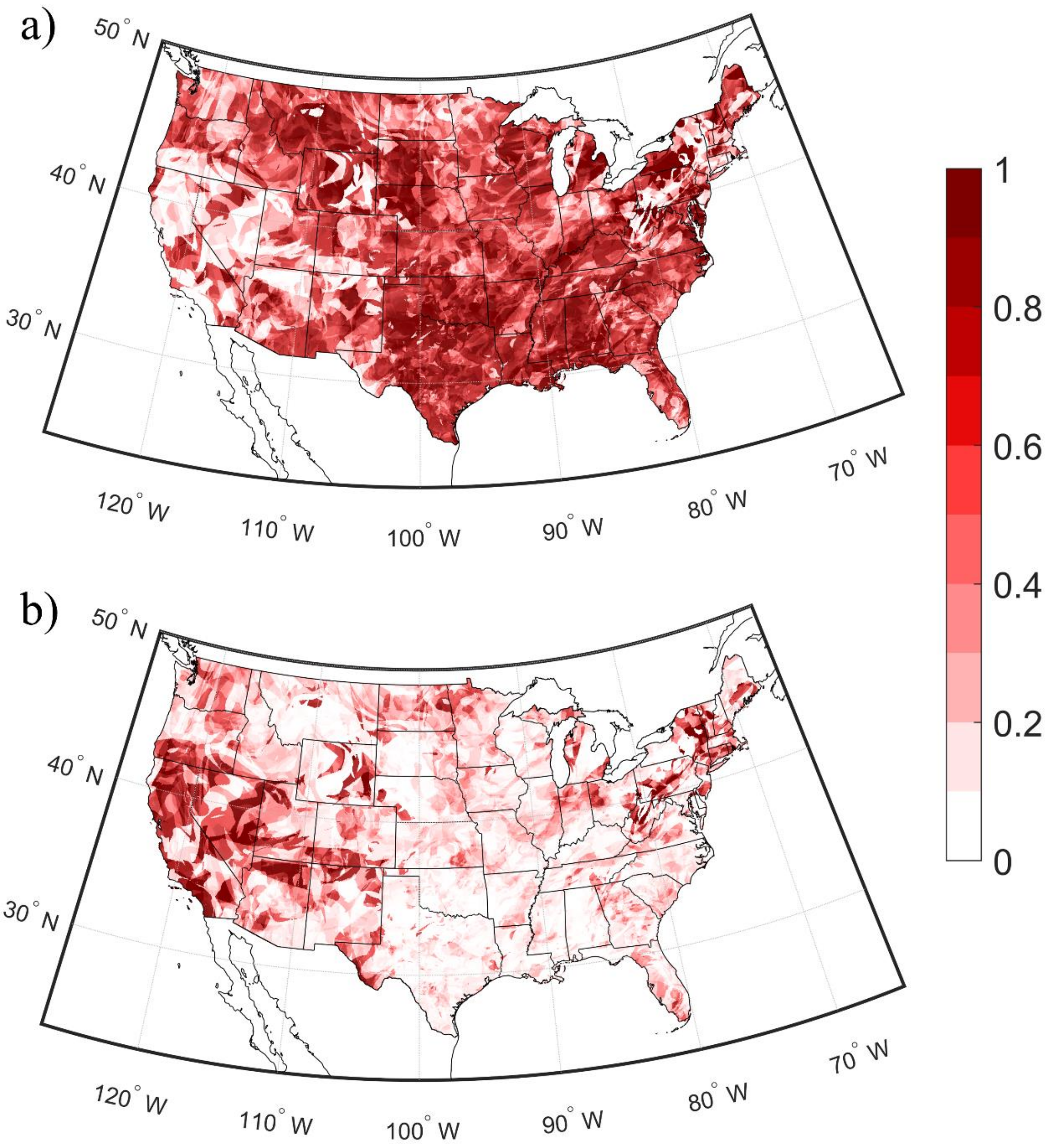


Figure 5. Relative proportions of flash and non-flash drought based on the USDM drought severity data, 2000-2019. Results are shown for a) proportion of flash drought events to all drought events, and b) proportion of non-flash drough tevents to all drought events.

In grid points to the west of the 100th meridian, flash drought was active for around 400 weeks in many places (Figure 6). That is equivalent to almost 100 months spent in drought in the 20 years from 2000-2019. There is a similar pattern with non-flash drought as well, but areas of non-flash drought are concentrated more in California, Nevada, Utah, Arizona, and New Mexico whereas the area of high flash drought activity is concentrated in central and southern U.S. There is extensive research about the prolonged precipitation deficits causing extensive slow-developing persistent droughts along the west coast that can last years (Andreadis & Lettenmaier 2006; Wise at al. 2016) and the central U.S. has fallen victim to flash droughts most often (Chen et al. 2019). An interesting feature of flash drought can be seen in Georgia, South Carolina, and Alabama. This area has a greater number of flash drought events and thus spent more weeks over the 20-year period in flash drought. The same pattern can be seen with the number of weeks spent in non-flash drought, but the pattern is much more exaggerated with flash drought events. When flash and non-flash events are combined, both patterns are exaggerated. The area west of the 100th meridian and the area around Georgia both have spent much more time in drought relative to the rest of the study area.

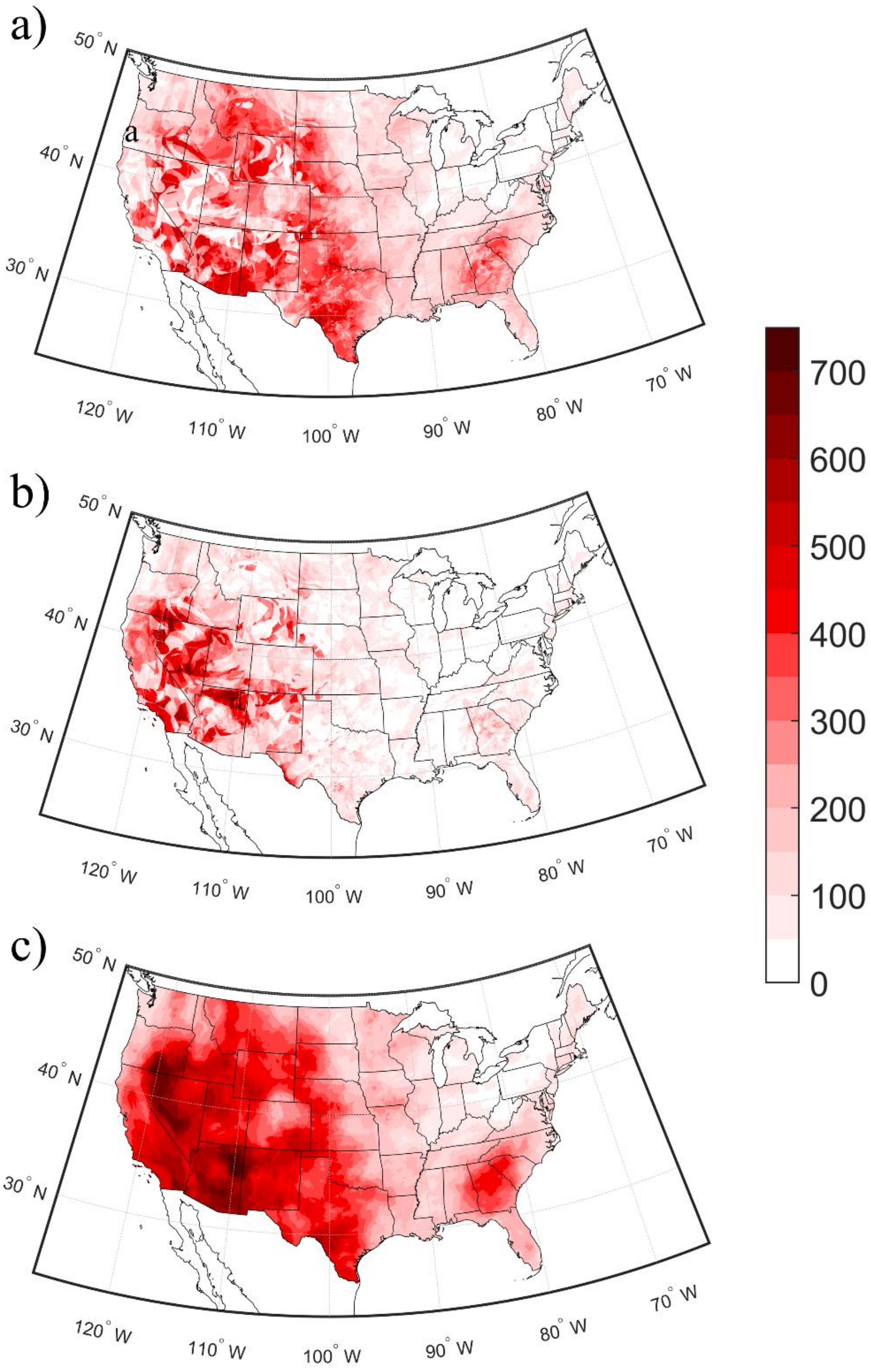


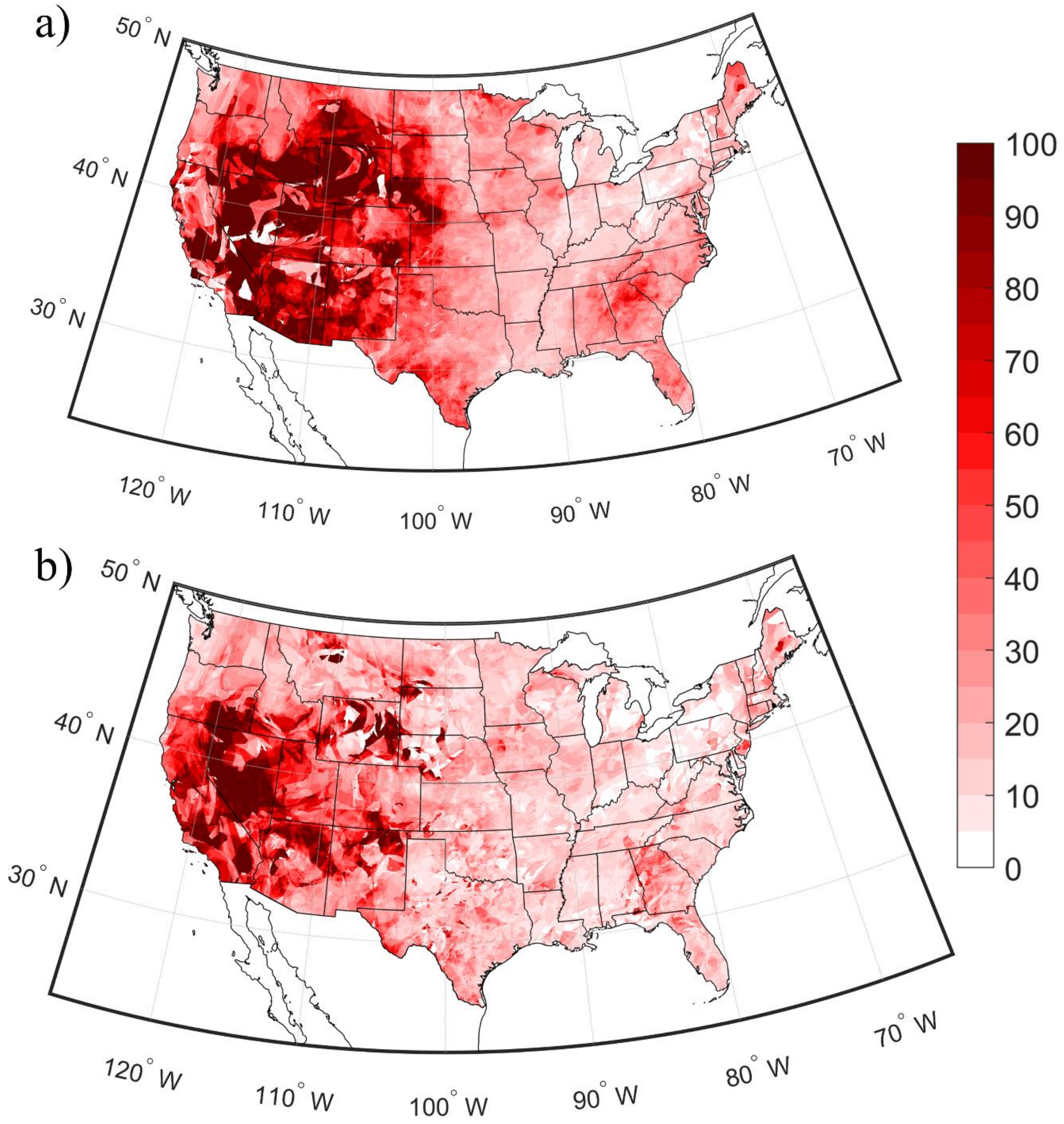
Figure 6. Total number of weeks in drought from the USDM drought severity data, 2000-2019. Total number of weeks over 20 years of data is 1044 weeks. Results are shown for a) flash drought, b) non-flash drought, and c) all drought.

A similar pattern for the mean length of flash and non-flash drought (Figure 8) can be seen west of the 100th meridian apart from the Northwest in which flash drought events last longer on average than non-flash events. Flash droughts last longer in the Georgia area as well. The pattern for mean length of flash droughts is much smoother in its transitions from areas to area average length to areas of low average length whereas the mean length of non-flash drought seems very erratic, and the patterns are much less defined. The reason for this, as seen in Figure 1 and will be further highlighted later, is that there are fewer non-flash drought events leading to a very small sample size in many grid cells.

The mean and median length maps (Figure 8 and Figure 7 respectively) are similar in many ways. The one point of interest is in the southern United States. For the general southern U.S., the mean is greater than the median, suggesting that there were a few long droughts that impacted the mean. However, our previous area of interest in the Georgia, South Carolina, and Alabama regions has a consistent mean/median duration suggesting that the distribution of flash drought event lengths is not skewed in that small area.

The area to the west of the 100th meridian has spent many more weeks in drought between 2000-2019 than the area to the east of the 100th meridian. Generally, the western United States experiences a larger proportion of non-flash drought to flash droughts, and the droughts in this region last longer regardless of event classification. The rest of the United States experiences a greater proportion of flash droughts to non-flash droughts that generally do not last as long as the west except for a hotspot in Georgia reaching into east Alabama and up into western South Carolina. The occurrence of flash drought events is greater in the Southwest region ranging from about 8 to 18 recorded events. Parts of the South, specifically Mississippi, Alabama, Georgia, South Carolina, and the Florida panhandle, also experienced an increased number of flash drought events ranging from about 6 to 14 events per grid cell.

Figure 7. Mean length (in weeks) of drought events based on the USDM drought severity data, 2000-2019. Results are shown for a) flash drought, and b) non-flash drought.



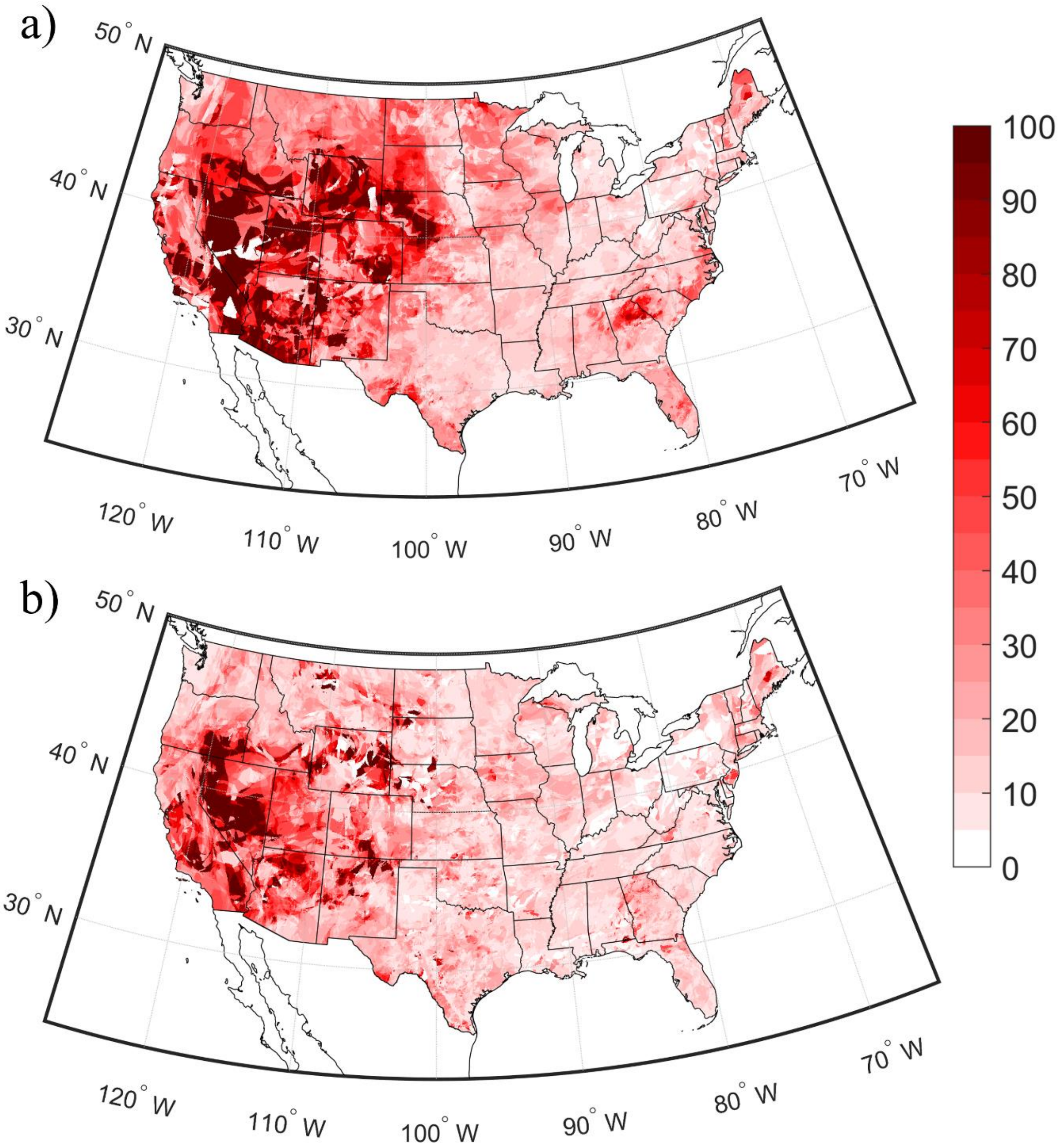


Figure 8. Median length (in weeks) of drought events based on the USDM drought severity data, 2000-2019. Results are shown for a) flash drought, and b) non-flash drought.

4.2.2 Regional Analysis

A combination of flash and non-flash drought activity was most prominent in the Northwest, Plains, Southwest, and South regions of the CONUS (refer to section 3.5). Therefore, these regions were chosen for a closer comparative analysis to discover any difference in flash and non-flash drought characteristics between the regions.

Figure 9 shows the number of flash or non-flash events per grid cell in each region. The Northwest and Plains regions have the fewest number of flash drought and non-flash drought events. More grid cells in the Northwest and Plains had 5 non-flash drought events than flash drought events. More grid cells had 6, 7, 8, or 9 flash drought events than non-flash drought events. Grid cells are slightly more likely to experience more flash drought events than non-flash drought events in these regions. The Southwest has the most grid cells with 5 or 6 non-flash drought events and the most grid cells having between 7 and 15 flash drought events. The Southwest had no grid cells with 11 or more non-flash drought events. The number of non-flash drought events in the Southwest and South are positively skewed to a much greater degree than flash drought events. A grid cell in the South or Southwest is more likely to have a higher number of flash drought events than non-flash drought events. The Northwest and Plains have a similar number of flash and non-flash droughts in each grid cell.

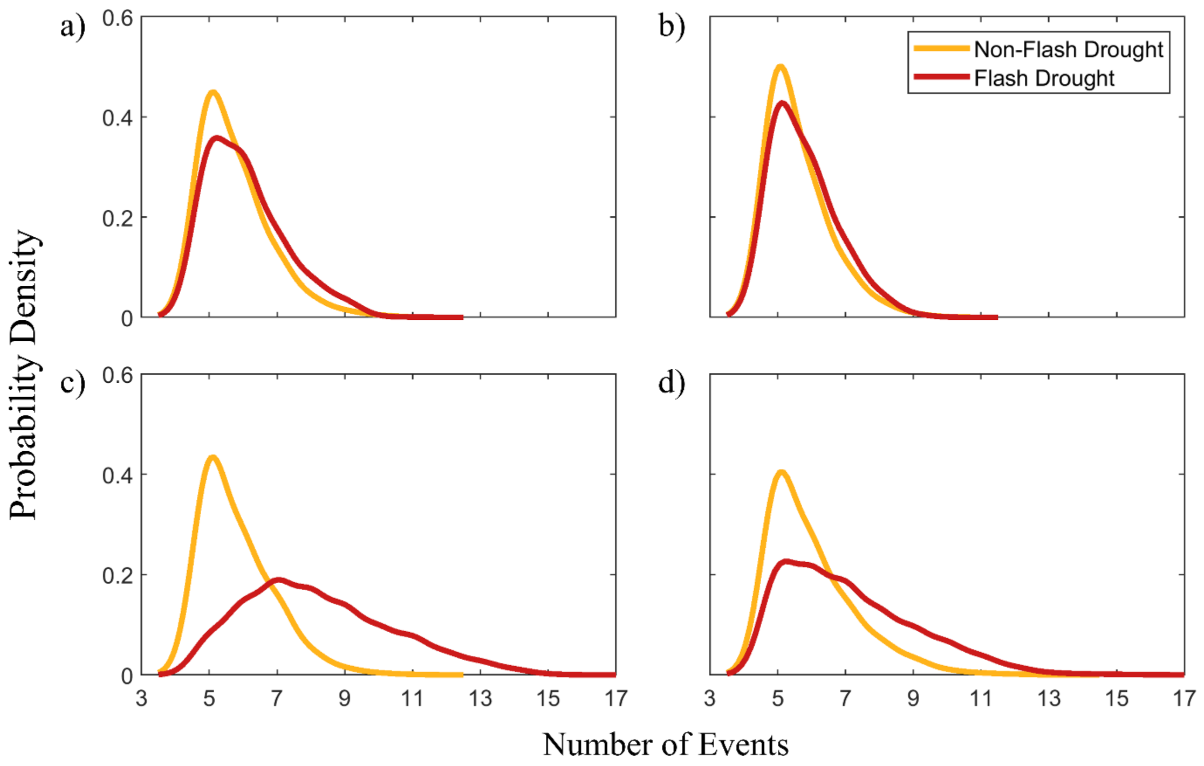


Figure 9. Number of drought events per grid cell based on the USDM drought severity data, 2000-2019. Results are shown for a) Northwest, b) Plains, c) Southwest, and d) South.

The total amount of weeks (out of 1044) spent in flash and non-flash drought per grid cell is shown in Figure 10. The length of the non-flash drought events is positively skewed in every region. Each region has spent more time in flash drought than in non-flash drought. In the Northwest, most grid cells have spent between 80 and 120 weeks in non-flash drought. The number of weeks each grid cell has spent in flash drought is much more variable for every region. The variability suggests that there may be intraregional differences that cause some areas within the region to experience either a greater number or longer flash drought events. Overall, all four regions have spent more weeks in flash drought, with many areas having double or triple the number of flash drought events compared to non-flash drought events.

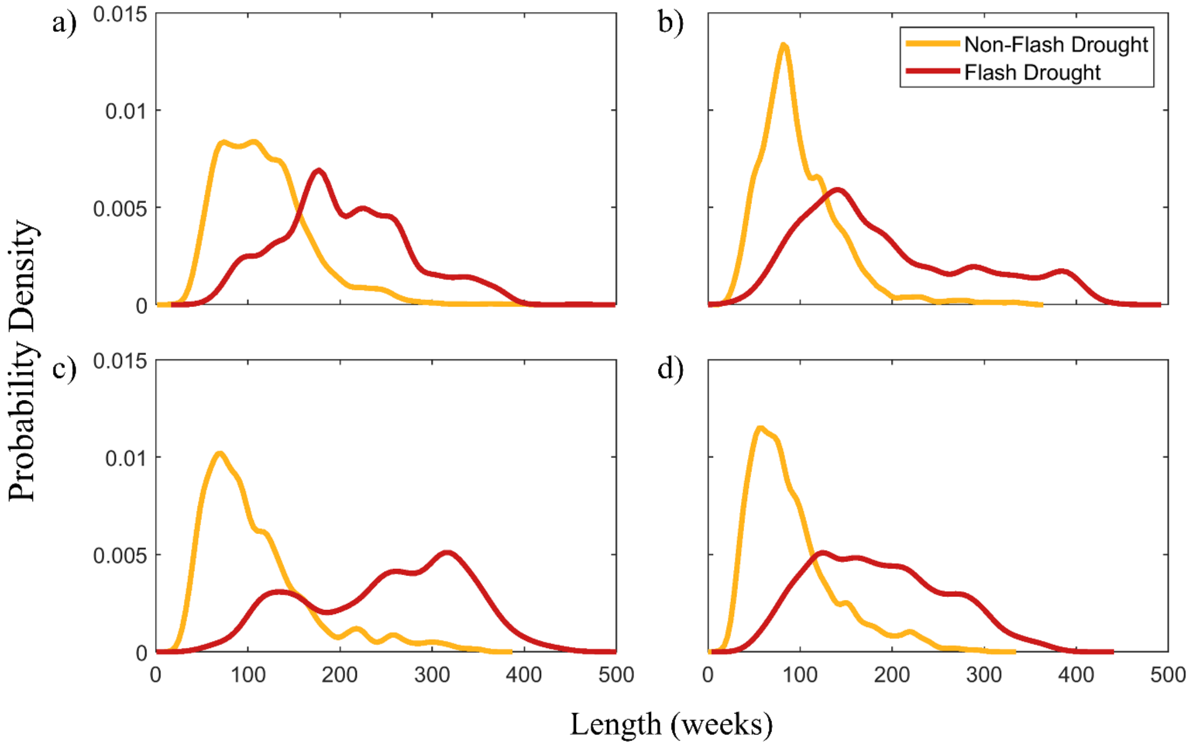


Figure 10. Frequency of length (in weeks) of drought events by region based on the USDM drought severity data, 2000-2019. Results are shown for a) Northwest, b) Plains, c) Southwest, and d) South.

It is not possible to tell from Figure 10 alone whether the variability in length each grid cell spends in flash or non-flash drought events is caused by a greater number of drought events or a longer length of drought events. To determine the length of each drought event, the mean event length is shown in Figure 11. In all regions, the mean non-flash drought length per grid cell is more positively skewed than flash drought. In all regions, a flash drought event is more likely to be longer than a non-flash drought event. In the Southwest and South, most grid cells had a mean length of non-flash drought events between 4 and 18 weeks, but there were many grid cells where median flash drought length in these regions was about 20 weeks.

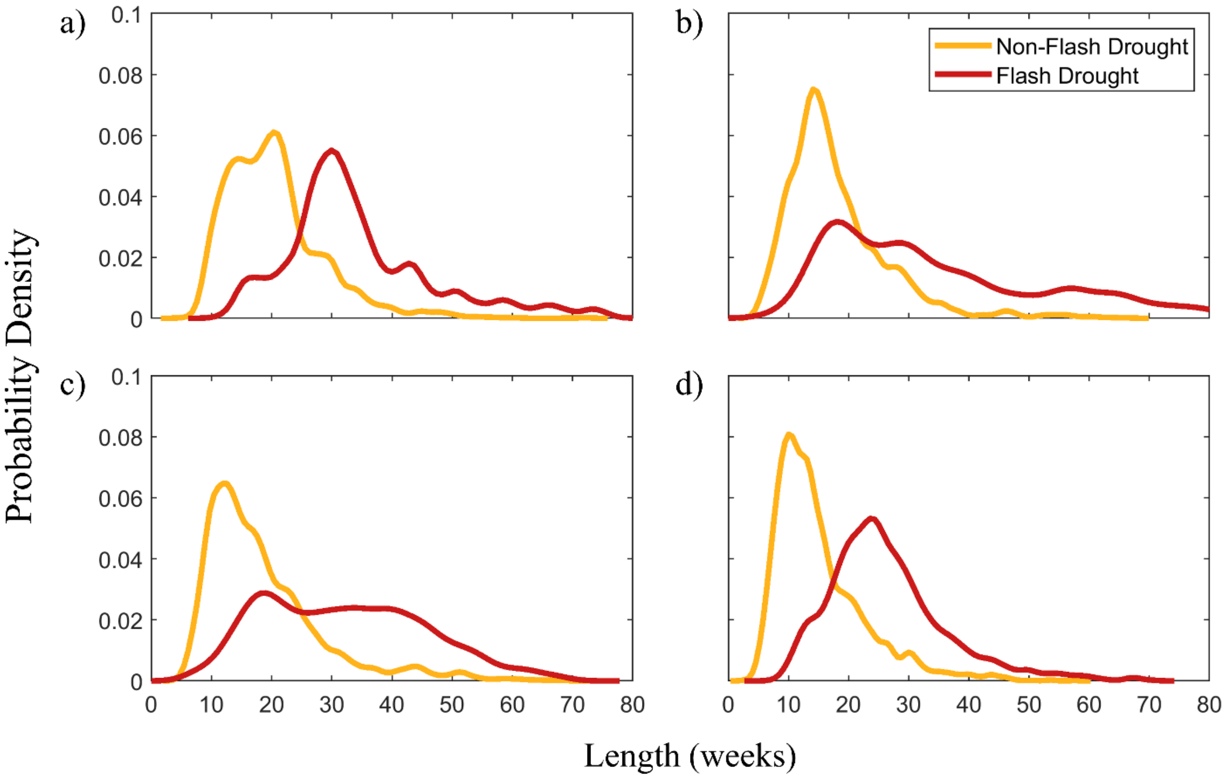


Figure 11. Mean length (in weeks) of drought events based on the USDM drought severity data, 2000-2019. Results are shown for a) Northwest, b) Plains, c) Southwest, and d) South.

4.3 Antecedent Meteorological Conditions Associated with Flash and Non-Flash Drought

Understanding the meteorological conditions associated with flash drought and non-flash drought events is essential to being able to eventually predict a flash drought event possibly weeks before it occurs. This section aims to compare the potential evapotranspiration (PET), vapor pressure deficit (VPD), maximum daily temperature (T_{max}), and minimum daily temperature (T_{min}) between flash drought, non-flash drought, and no drought up to 6 weeks before an event. Anomalies are used for these variables to show the departure from the mean leading up to an event.

In order to give context to the following figures that utilize anomalies, Table 2 shows the maximum, minimum, and mean of each of the meteorological variables and each region. The grid points included in this statistical summary are the same grid points highlighted in Figure 3 and Table 1 T_{min} and T_{max} both have the largest ranges out of the variables and VPD has the smallest range. This pattern will be reflected in the figures later in this section. The Northwest had the lowest mean value of VPD, T_{min}, and T_{max} with 0.83 kPa, 5.45 °C, and 18.99 °C, respectively. The Plains had the lowest mean VPD. The highest means for all the variables were either in the South (VPD, T_{min}, and T_{max}) or Southwest (PET). It is important to note that the means listed in Table 2 are not the same number that would be represented by an anomaly of 0 in the figures that follow. Please refer to section 3.6 for more detail about how anomalies were calculated.

Table 2. Maximum, minimum, and mean values for each meteorological variable in each region 2000-2019. Statistics are calculated using the grid points that meet the criteria for adequate sample size (figure X).

Northwest				
	PET (mm)	VPD (kPa)	T_{min} (°C)	T_{max} (°C)
Mean	3.72	0.83	5.43	18.99
Maximum	12.50	5.60	30.25	46.95
Minimum	0.10	0.00	-38.05	-27.65
Plains				
	PET (mm)	VPD (kPa)	T_{min} (°C)	T_{max} (°C)
Mean	4.74	1.15	9.19	23.52
Maximum	16.80	7.71	33.85	50.65
Minimum	0.10	0.00	-31.25	-19.45
Southwest				
	PET (mm)	VPD (kPa)	T_{min} (°C)	T_{max} (°C)
Mean	5.71	1.17	9.46	23.74
Maximum	15.70	10.30	43.85	53.95
Minimum	0.10	0.00	-31.75	-17.65
South				
	PET (mm)	VPD (kPa)	T_{min} (°C)	T_{max} (°C)
Mean	4.59	1.44	15.66	29.47
Maximum	13.50	7.94	36.55	50.25
Minimum	0.20	0.00	-24.35	-11.75

4.3.1 Potential Evapotranspiration (PET)

Figure 12 shows the boxplot distributions of PET anomalies for each event type and region. The distribution of anomalies for non-drought weeks tends to be centered around 0 and is more likely to be characterized by both positive and negative anomalies. Flash and non-flash drought weeks tend to have a similar range but are more likely to have higher anomalies than non-drought. The broad pattern for each week and each region of the PET boxplot is that the flash drought events have the greatest median anomaly followed by non-flash drought events and then no drought. This pattern is strongest the first and second week before an event and becomes less and even disappears the farther out from an event. There are a few exceptions to this generalization. For the sixth week prior to an event in the Southwest, the median for non-flash drought fell below the median for no drought event. In the Southwest, there is only a very small difference in medians of PET anomalies between flash and non-flash drought events in the fourth and fifth week leading up to the event. Besides a few outliers, the upper range of the anomalies is more positive for flash drought than non-flash drought in every region and every week. Further supporting that a higher PET is more likely to be seen by a flash drought event.

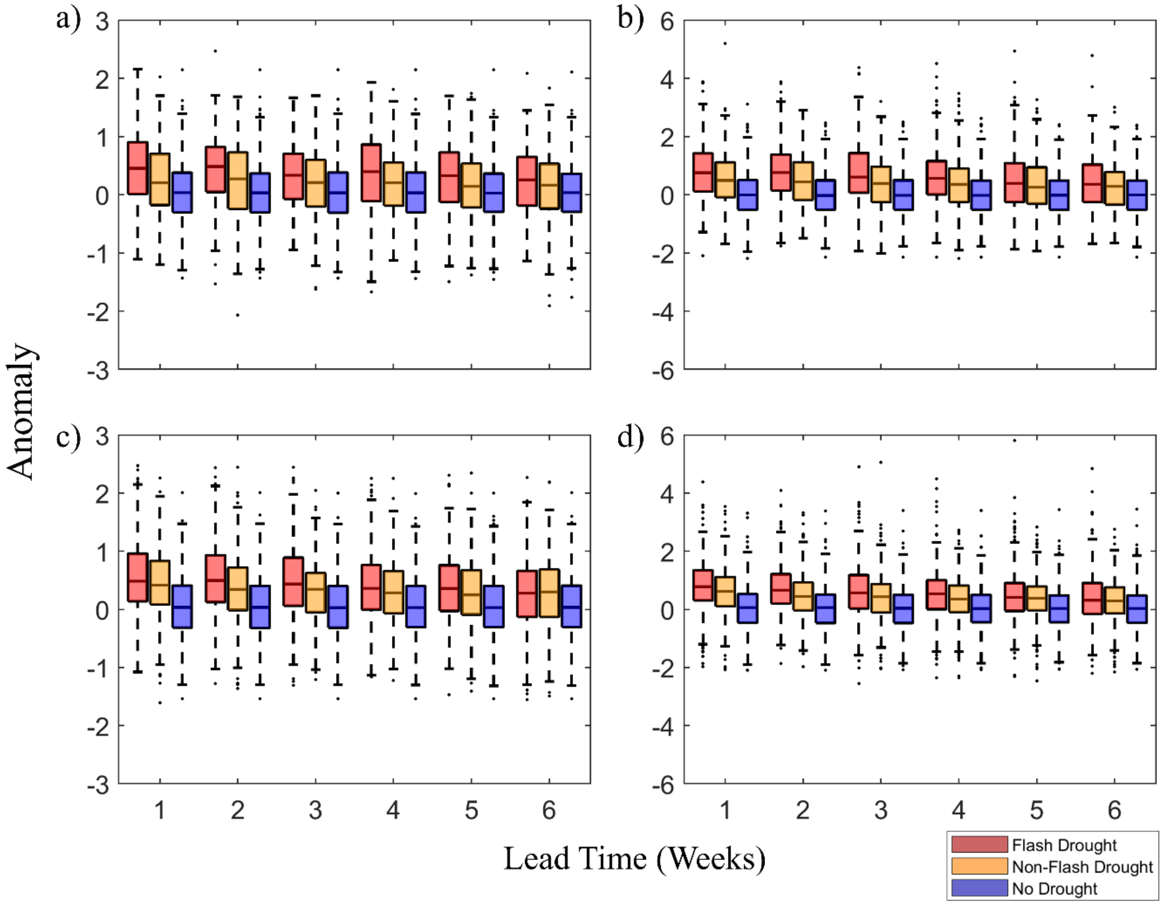


Figure 12. Distribution of potential evapotranspiration (mm) 1-week anomalies 1- through 6-weeks before an event shown with boxplots for flash (red), non-flash (yellow) and no drought (blue) events. Note that y-axes differ between panels. Results are shown for a) Northwest, b) Plains, c) Southwest, and d) South.

Figure 13 shows the mean PET anomalies for one to six weeks before an event type for each region. The mean for non-drought weeks stays very constant around 0. Mean PET before a flash drought is greater than non-flash drought and non-drought weeks for all lead times and regions apart from the sixth week in the South where mean PET for non-flash drought exceeds flash drought. Generally, the farther out from an event, the more similar the means for the event types. As the lead time decreases, the differences between the means of the three event types increase. The greatest difference between flash drought and non-flash drought occurs in the

Plains. While in the South, mean PET for flash drought and non-flash drought are very similar for every lead time. In the Northwest, the mean PET for flash drought is greater than the other event types for every week for the six weeks before an event, however, they are very close. The other regions have a similar pattern to the median where flash drought is greatest followed by non-flash drought and no drought events. Anomalous PET values are most obvious in the Plains and the Southwest for up to six weeks before an event. It is harder to distinguish in the other regions.

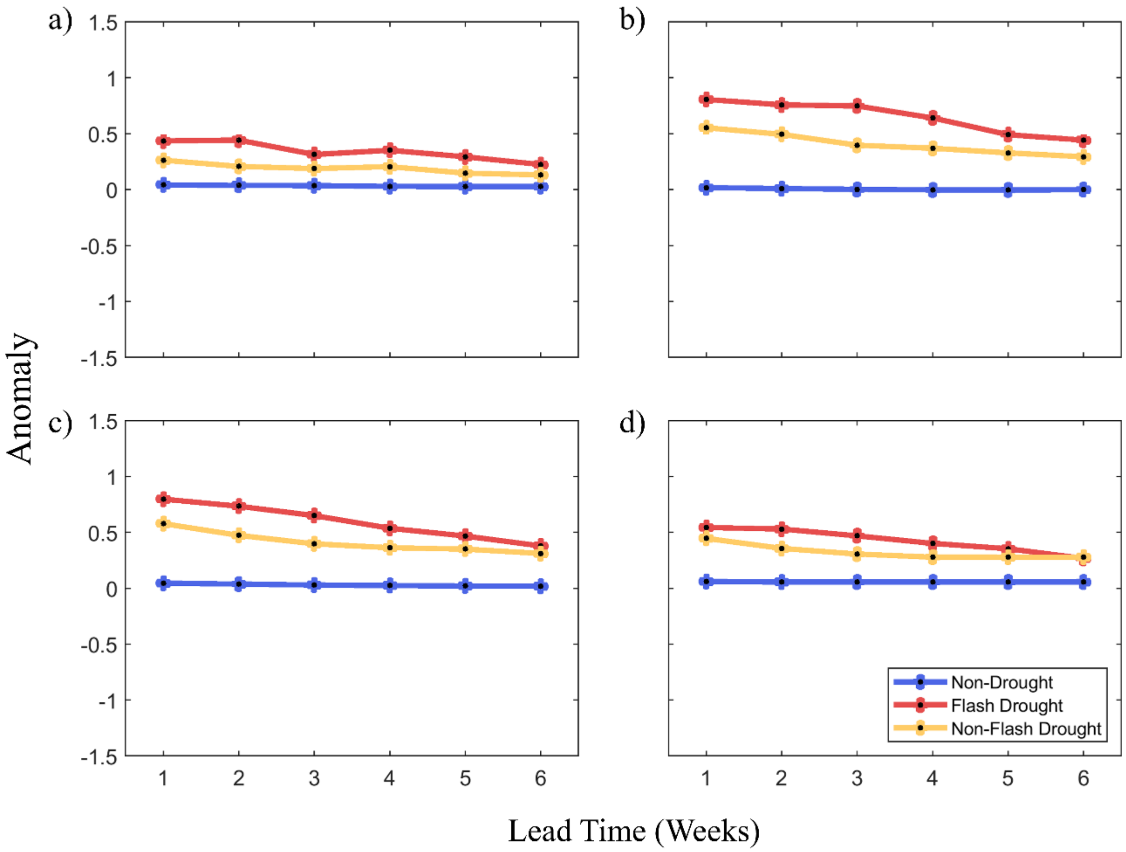


Figure 13. Trend of potential evapotranspiration (mm) 1-week mean anomalies 1- through 6-weeks before an event shown for flash (red), non-flash (yellow) and no drought (blue) events. Results are shown for a) Northwest, b) Plains, c) Southwest, and d) South.

Table 3 shows the p-values for a t-test in which the hypothesis is that two means for PET are equal. The alpha value with Bonferroni correction is 0.00017. As expected, for each region mean PET for flash drought and non-drought are significantly different. In the Plains, Southwest, and South, the difference between means of non-flash drought and non-drought are significantly different for all lead times. In the Northwest, only the lead times of one and three weeks are significantly different. For the comparison of non-flash and flash drought means, the p-values for weeks one through four are all less than 0.05. With the Bonferroni correction, the only weeks that have significantly different means are weeks one and four in the Northwest, week three in the Plains, and weeks two and three in the Southwest. PET has the potential to be a good variable to predict a flash drought over a non-flash drought, but it is not completely reliable.

Table 3. P-values resulting from a two-sample T-test for PET shown for the Northwest, Plains, Southwest, and South. Results are shown for each lead time and each combination of flash and non-flash, non-flash and non-drought, and non-flash and non-drought. Highlighted in yellow are the P-values that are below alpha (0.00017). See section 3.6 for more detail about how the p-values and alpha were calculated.

	Northwest			Plains		
	Flash Non-Drought	Non-Flash Non-Drought	Flash Non-Flash	Flash Non-Drought	Non-Flash Non-Drought	Flash Non-Flash
1-week	0.00000	0.00000	0.00968	0.00000	0.00000	0.00255
2-week	0.00000	0.00075	0.00059	0.00000	0.00000	0.00112
3-week	0.00000	0.00115	0.04112	0.00000	0.00000	0.00003
4-week	0.00000	0.00012	0.03270	0.00000	0.00000	0.00145
5-week	0.00000	0.00901	0.02434	0.00000	0.00000	0.04517
6-week	0.00013	0.02331	0.13785	0.00000	0.00000	0.05444
	Southwest			South		
	Flash Non-Drought	Non-Flash Non-Drought	Flash Non-Flash	Flash Non-Drought	Non-Flash Non-Drought	Flash Non-Flash
1-week	0.00000	0.00000	0.00034	0.00000	0.00000	0.04187
2-week	0.00000	0.00000	0.00001	0.00000	0.00000	0.00022
3-week	0.00000	0.00000	0.00005	0.00000	0.00000	0.00038
4-week	0.00000	0.00000	0.00402	0.00000	0.00000	0.00632
5-week	0.00000	0.00000	0.04646	0.00000	0.00000	0.10029
6-week	0.00000	0.00000	0.27109	0.00000	0.00000	0.82428

4.3.2 Vapor Pressure Deficit (VPD)

Figure 14 shows the boxplot distribution of VPD anomalies for each event type and region. The same trends as the PET distribution can be seen with VPD. Non-drought weeks have a consistent median around 0 and a consistently small range. Flash drought tends to have a greater median and a slightly larger range than non-drought and non-flash drought has a smaller range. The median values of VPD follow roughly the same pattern seen in PET. The median of flash drought is greater than non-flash drought and no drought for all six weeks in the Northwest and Plains, and four weeks in the Southwest and South. The more weeks out from an event, the smaller the difference between the median of flash drought, non-flash drought, and no drought gets. At six weeks it becomes more difficult to distinguish between the means for the events.

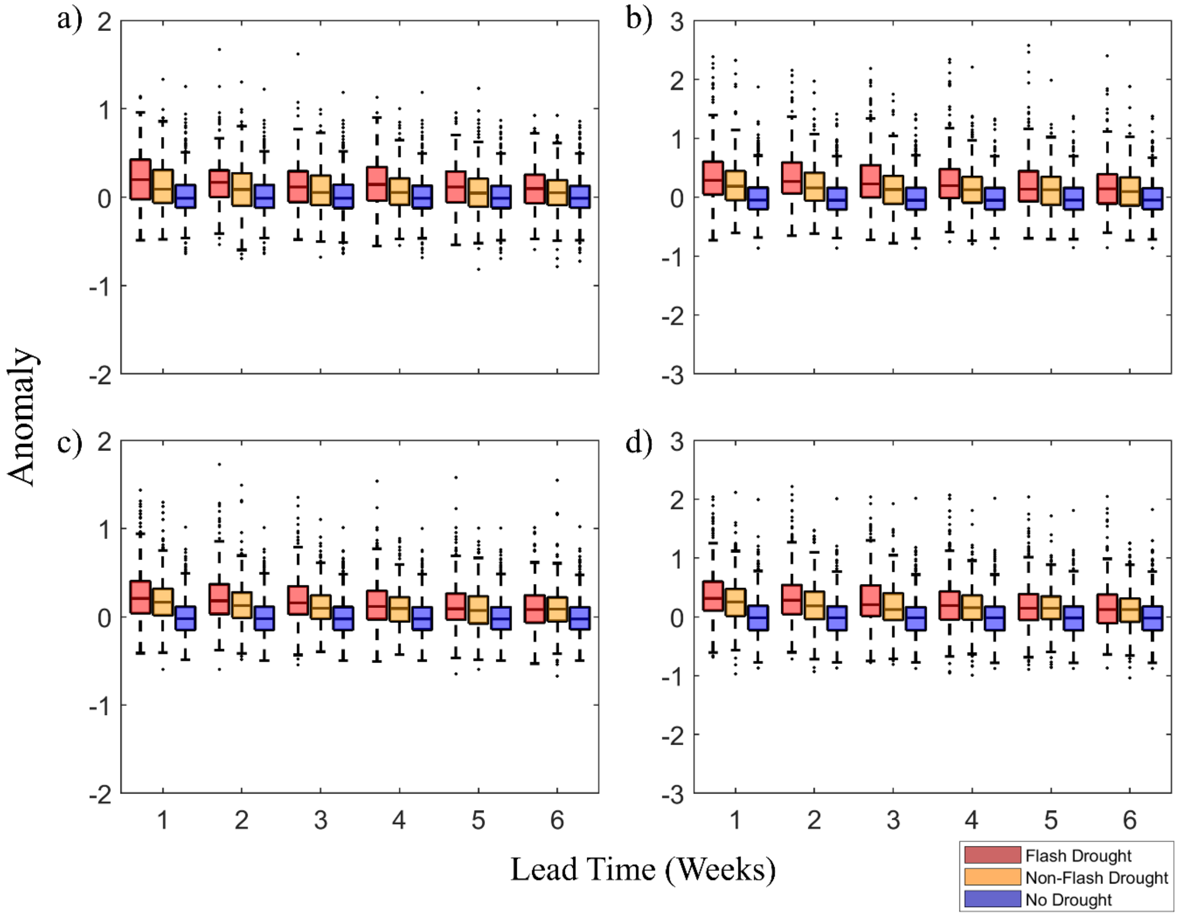


Figure 14. Distribution of vapor pressure deficit (kPa) 1-week anomalies 1- through 6- weeks before an event shown with boxplots for flash (red), non-flash (yellow) and no drought (blue) events. Note that y-axes differ between panels. Results are shown for a) Northwest, b) Plains, c) Southwest, and d) South.

Figure 15 shows the mean VPD anomalies for one to six weeks before an event. Like PET, mean VPD for flash drought is higher than non-flash which is higher than non-drought except for the sixth week in the South where flash drought is slightly lower than non-flash drought. In the Plains, the difference in mean anomalies of VPD for flash drought and non-flash drought or no drought is much greater than in the other region. The Southwest and South are very similar. Flash drought and non-flash drought are both very distinguished from non-drought but are less distinguishable from one another. Nonetheless, mean VPD for flash drought is higher than non-flash drought. This is consistent with the finding that flash drought requires lower humidity and higher atmospheric demand than non-flash droughts. However, non-flash droughts still have below average humidity and above average PET, but it does not become apparent until one to three weeks before an event depending on the region. Also, the South does not show a lot of difference between mean VPD and PET anomalies for flash drought and non-flash drought, which may suggest that it will be more difficult to delineate and predict a flash drought as compared to a non-flash drought in this region.

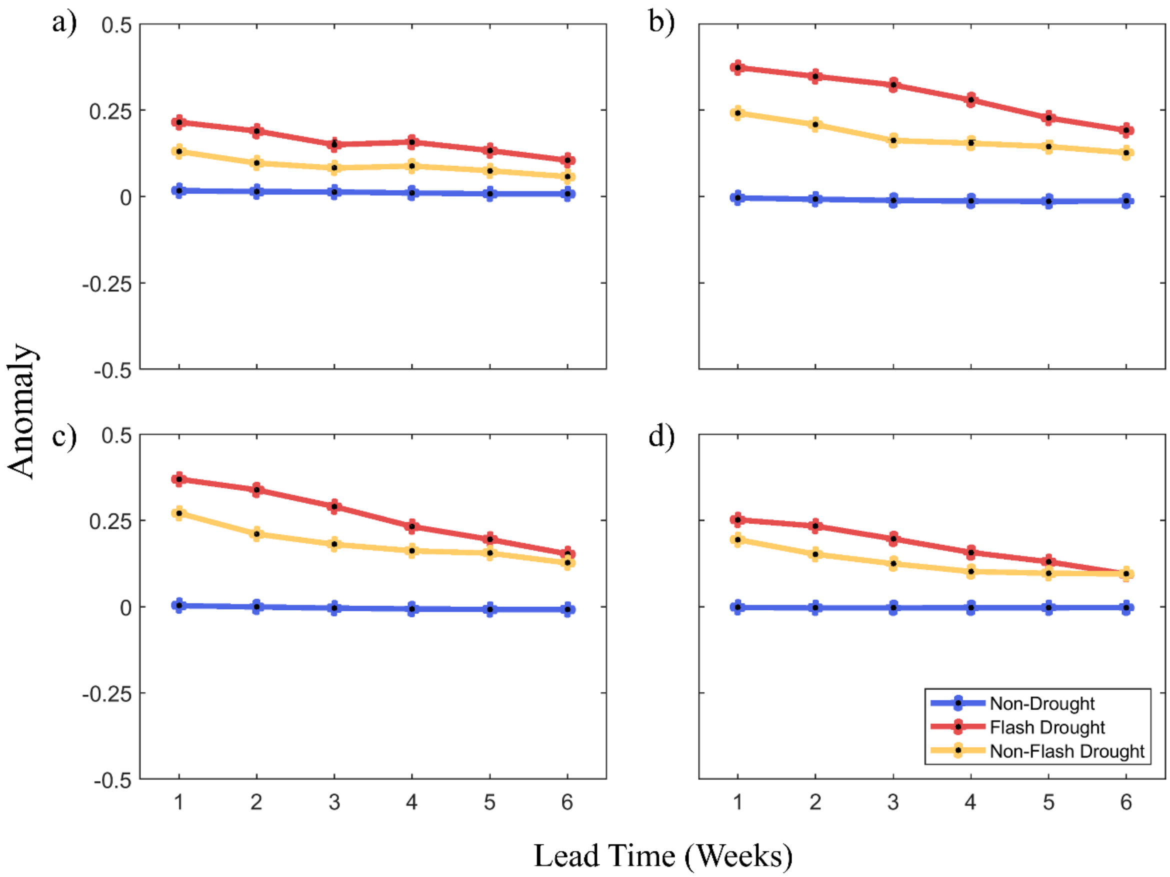


Figure 15. Trend of vapor pressure deficit (kPa) 1-week mean anomalies 1- through 6- weeks before an event for flash (red), non-flash (yellow) and no drought (blue) events. Results are shown for a) Northwest, b) Plains, c) Southwest, and d) South.

Table 4 shows the p-values representing the significance for the means for each week and region of VPD. Like PET, the first four weeks for the Northwest, Plains, and Southwest, as well as the first three weeks in the South all have p-values below 0.05, which would be significant if not for the correction for many tests, which brought the alpha value down to 0.00017. The only statistically significant difference in means occurs between flash and non-flash drought in the second week in the Southwest and the third week in the Plains.

Table 4. P-values resulting from a two-sample T-test for VPD shown for the Northwest, Plains, Southwest, and South. Results are shown for each lead time and each combination of flash and non-flash, non-flash and non-drought, and non-flash and non-drought. Highlighted in yellow are the P-values that are below alpha (0.00017). See section 3.6 for more detail about how the p-values and alpha were determined.

	Northwest			Plains		
	Flash Non-Drought	Non-Flash Non-Drought	Flash Non-Flash	Flash Non-Drought	Non-Flash Non-Drought	Flash Non-Flash
1-week	0.17118	0.53760	0.01012	0.00345	0.05129	0.00101
2-week	0.23777	0.72938	0.00430	0.00501	0.07766	0.00022
3-week	0.44208	0.86942	0.02551	0.00517	0.11044	0.00003
4-week	0.33189	0.72795	0.02398	0.01326	0.12187	0.00140
5-week	0.36652	0.70648	0.05295	0.03391	0.13186	0.02565
6-week	0.50910	0.81915	0.10025	0.06922	0.18303	0.06427

	Southwest			South		
	Flash Non-Drought	Non-Flash Non-Drought	Flash Non-Flash	Flash Non-Drought	Non-Flash Non-Drought	Flash Non-Flash
1-week	0.00204	0.04041	0.00081	0.01131	0.06501	0.01267
2-week	0.00382	0.12528	0.00000	0.01642	0.15631	0.00017
3-week	0.00986	0.15572	0.00018	0.05775	0.30411	0.00031
4-week	0.03175	0.16103	0.01075	0.17152	0.48373	0.00561
5-week	0.06757	0.15846	0.13496	0.27828	0.49320	0.10230
6-week	0.14773	0.24021	0.33317	0.48390	0.48044	0.97938

4.3.3 Minimum Daily Temperature (T_{min})

Like PET and VPD, the distribution of non-drought week T_{min} anomalies (Figure 16) is relatively similar, if not smaller than flash and non-flash drought. Median anomaly for non-drought stays consistently around 0 regardless of lead time. Unlike VPD and PET, there is not a discernable pattern in medians in minimum temperature. In the Southwest, median T_{min} for flash drought is lower than non-flash and non-drought. The minimum daily temperature is not a good variable for predicting flash drought events. There is very little difference in the median and interquartile range for the three event types regardless of lead time and region.

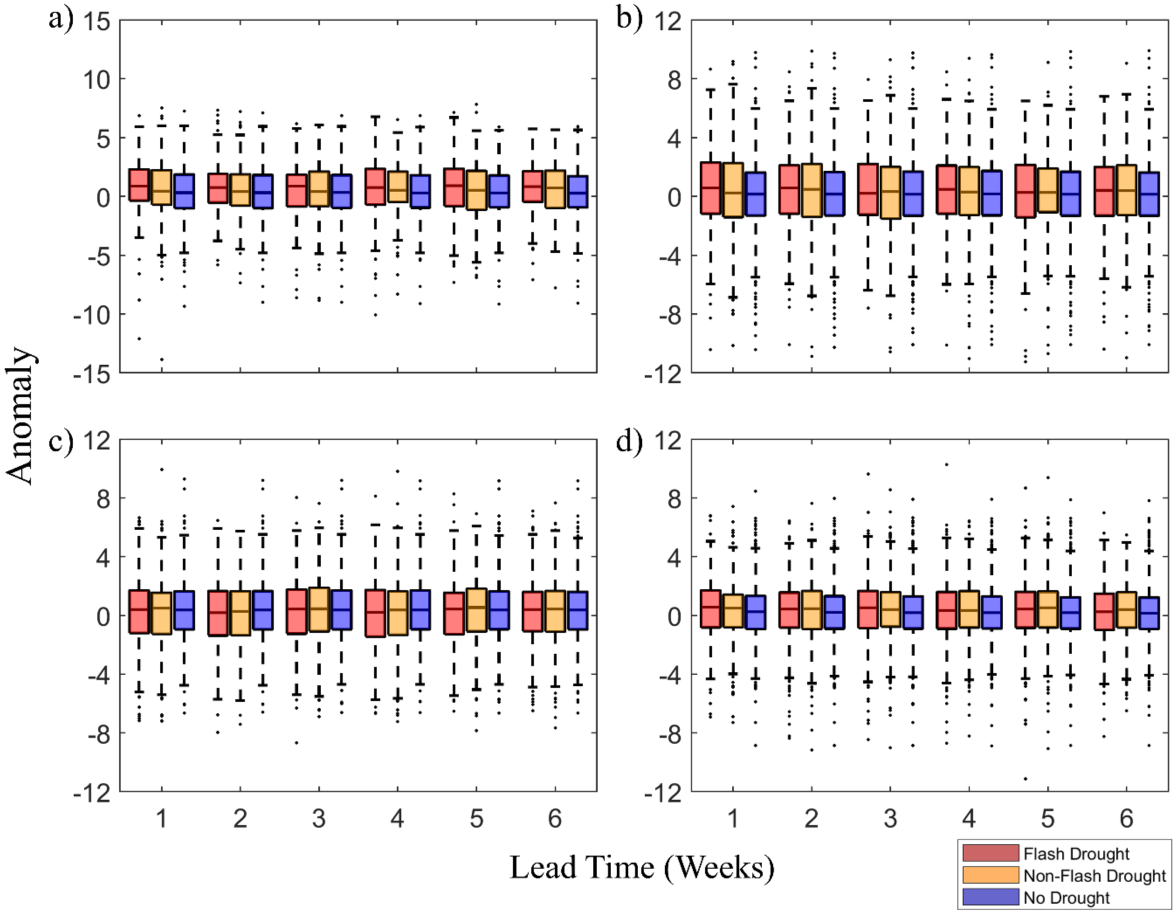


Figure 16. Distribution of minimum temperature (°C) 1-week anomalies 1- through 6- weeks before an event shown with boxplots for flash (red), non-flash (yellow) and no drought (blue) events. Note that y-axes are not consistent. Results are shown for a) Northwest, b) Plains, c) Southwest, and d) South.

The mean anomalies for T_{min} shown in Figure 17 do not show an obvious pattern like the boxplot for T_{min}. The Northwest and the Plains follow the general pattern seen in previous sections the closest. In the Northwest, the mean for flash drought is greater than non-flash drought for the week one and two and in the Plains, the mean for flash drought is barely greater than non-flash for the first five weeks. In the Southwest, the mean values for the three event types are very similar. Mean T_{min} for flash drought is higher than non-flash for the first two weeks before dropping below non-flash drought for weeks four through six. In the South, the mean T_{min} anomaly for flash drought and non-flash drought is lower than non-drought for all six weeks. Minimum temperature is generally too inconsistent to be able to link with the occurrence of flash or non-flash events for every region except possibly the Northwest a week or two before the onset of a flash drought event.

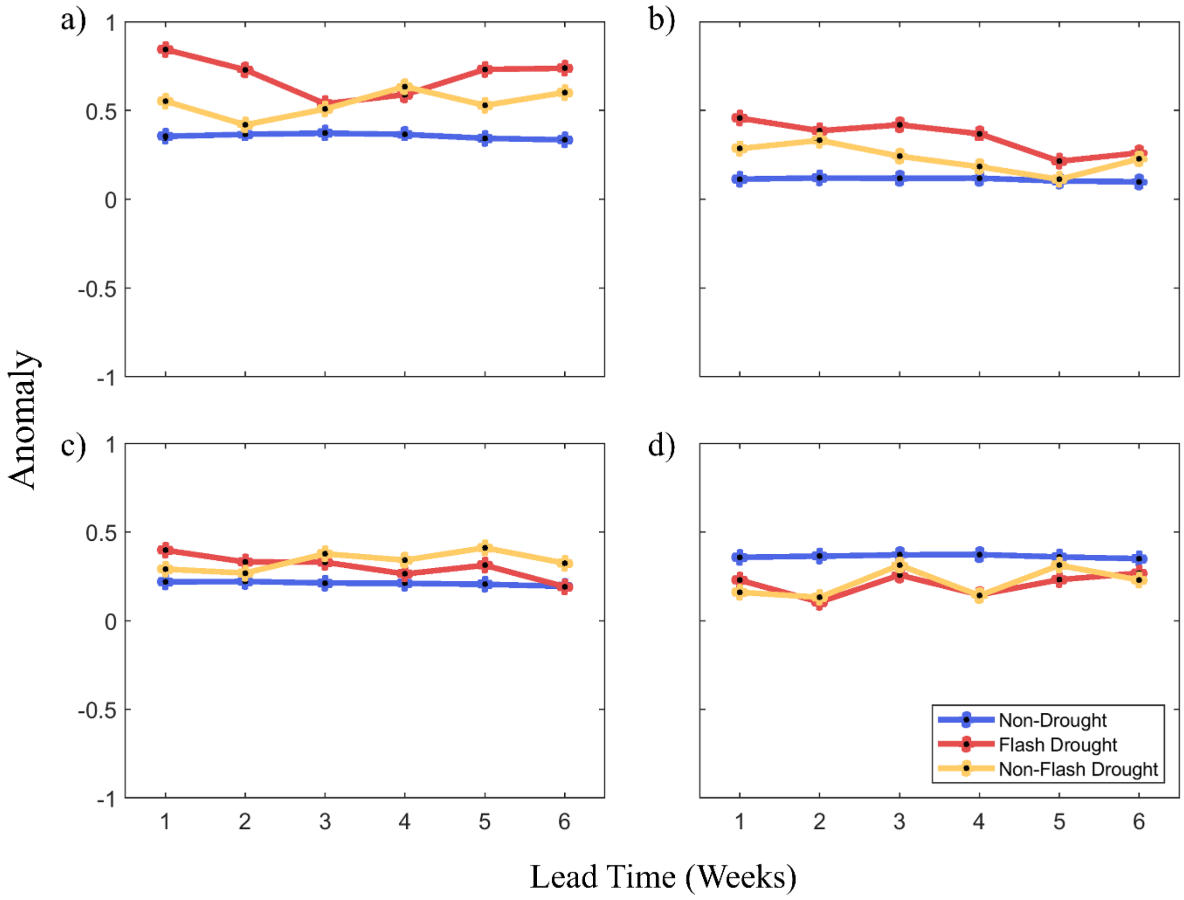


Figure 17. Trend of minimum temperature (°C) 1-week mean anomalies 1- through 6- weeks before an event shown for flash (red), non-flash (yellow) and no drought (blue) events. Results are shown for a) Northwest, b) Plains, c) Southwest, and d) South.

The boxplots and means for T_{min} anomalies were very similar and did not show any distinct patterns. The p-values in Table 4 show a similar story. There are no two means for any week or region that are significantly different, further supporting that T_{min} is not a reliable variable to use for flash drought or non-flash drought early warning.

Table 5. P-values resulting from a two-sample T-test for T_{min} shown for the Northwest, Plains, Southwest, and South. Results are shown for each lead time and each combination of flash and non-flash, non-flash and non-drought, and non-flash and non-drought. Highlighted in yellow are the P-values that are below alpha (0.00017). See section 3.6 for more detail about how the p-values and alpha were calculated.

	Northwest			Plains		
	Flash Non-Drought	Non-Flash Non-Drought	Flash Non-Flash	Flash Non-Drought	Non-Flash Non-Drought	Flash Non-Flash
1-week	0.02322	0.31824	0.28073	0.08085	0.40167	0.48926
2-week	0.06385	0.76600	0.19738	0.17302	0.29461	0.82617
3-week	0.42159	0.46175	0.90580	0.09177	0.53034	0.44281
4-week	0.34106	0.12989	0.86653	0.17007	0.74952	0.42883
5-week	0.07582	0.32048	0.44258	0.56464	0.96225	0.66695
6-week	0.03785	0.12547	0.56140	0.38395	0.49254	0.88167
	Southwest			South		
	Flash Non-Drought	Non-Flash Non-Drought	Flash Non-Flash	Flash Non-Drought	Non-Flash Non-Drought	Flash Non-Flash
1-week	0.58312	0.15167	0.47636	0.21143	0.39229	0.71368
2-week	0.72423	0.38288	0.69084	0.12013	0.08034	0.87745
3-week	0.22191	0.35943	0.76637	0.70674	0.44136	0.75709
4-week	0.32092	0.67798	0.61562	0.15190	0.13254	0.98249
5-week	0.12929	0.40877	0.54268	0.75851	0.37885	0.64952
6-week	0.31308	0.98601	0.35503	0.42866	0.56632	0.82267

4.3.3 Maximum Daily Temperature (T_{max})

The boxplot of T_{max} anomalies (Figure 18) shows a more distinguishable pattern than T_{min}. For every region, weeks one through four shows that the median for flash drought is greater than the median of non-flash drought, which is then greater than the median anomaly for no drought. After four weeks, it becomes more difficult to distinguish the medians from one another. Similar to T_{min}, the Northwest and the Plains show the most distinguishable pattern of median anomalies for flash, non-flash, and non-drought events. In the Southwest and South, T_{max} anomalies for flash and non-flash droughts are very similar.

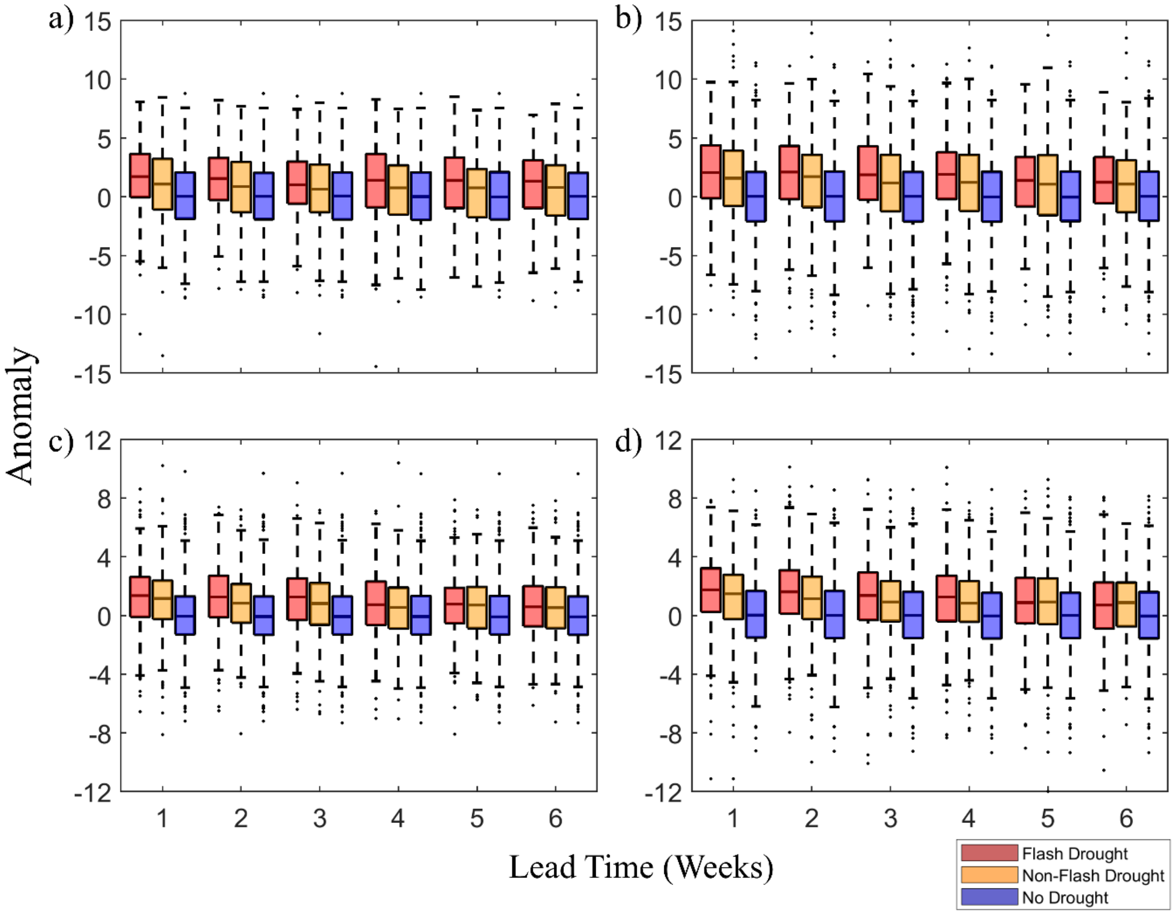


Figure 18. Distribution of maximum temperature (°C) 1-week anomalies 1- through 6- weeks before an event shown with boxplots for flash (red), non-flash (yellow) and no drought (blue) events. Note that y-axes are not consistent. Results are shown for a) Northwest, b) Plains, c) Southwest, and d) South.

Mean T_{max} anomalies shown in Figure 19 show that in the Northwest and Plains, the anomaly is greater than non-flash or no drought events for all six weeks. In the Southwest, mean T_{max} splits off from non-flash drought and no drought at the third week and the difference continues to increase until one week from a flash drought event. In the South, T_{max} for flash and non-flash drought split away from no drought at the fourth week, but mean anomaly for flash drought and non-flash drought do not become noticeably different until the second week before an event. The difference in mean anomalies for flash and non-flash drought is the most distinct in the Plains and Northwest, so using T_{max} to predict flash drought events may be useful in this area. In the South and Southwest, the mean anomalies for flash and non-flash drought are much more similar.

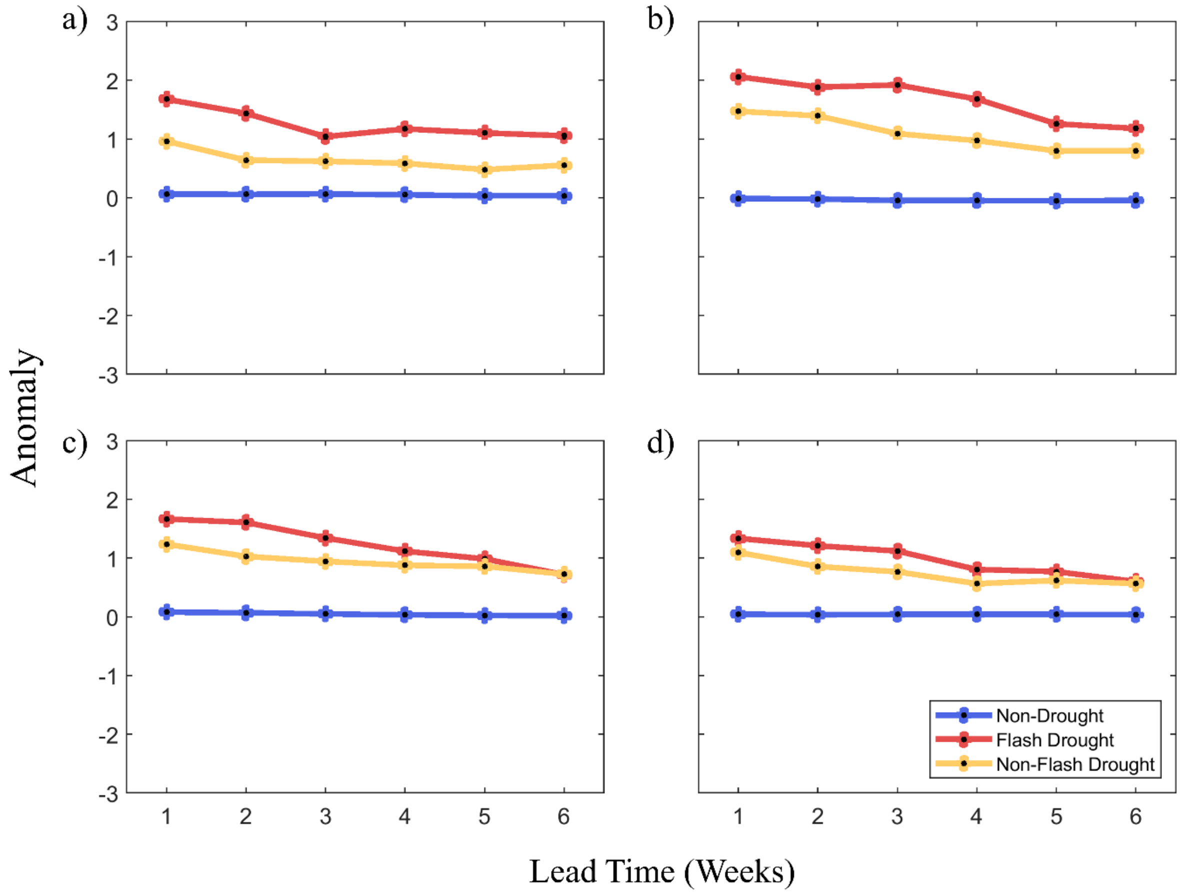


Figure 19. Trend of maximum temperature (°C) 1-week mean anomalies 1- through 6- weeks before an event shown for flash (red), non-flash (yellow) and no drought (blue) events. Results are shown for a) Northwest, b) Plains, c) Southwest, and d) South.

Like T_{min}, Table 6 shows that there is no significance in the difference between mean maximum temperature anomalies. This means that it cannot be confirmed that any of the means are different from one another. Based on the t-tests, maximum temperature is not a reliable variable for predicting flash drought events.

Table 6. P-values resulting from a two-sample T-test for T_{max} shown for the Northwest, Plains, Southwest, and South. Results are shown for each lead time and each combination of flash and non-flash, non-flash and non-drought, and non-flash and non-drought. Highlighted in yellow are the P-values that are below alpha (0.00017). See section 3.6 for more detail about how the p-values and alpha were calculated.

	Northwest			Plains		
	Flash Non-Drought	Non-Flash Non-Drought	Flash Non-Flash	Flash Non-Drought	Non-Flash Non-Drought	Flash Non-Flash
1-week	0.56919	0.45927	0.03757	0.23926	0.23167	0.06092
2-week	0.76579	0.93479	0.01541	0.86035	0.72752	0.11861
3-week	0.49512	0.69801	0.19000	0.46503	0.79131	0.00759
4-week	0.74655	0.99542	0.09284	0.73540	0.95523	0.02597
5-week	0.89503	0.75820	0.06232	0.62960	0.86812	0.13923
6-week	0.95068	0.64785	0.11884	0.67520	0.88708	0.20375

	Southwest			South		
	Flash Non-Drought	Non-Flash Non-Drought	Flash Non-Flash	Flash Non-Drought	Non-Flash Non-Drought	Flash Non-Flash
1-week	0.55784	0.67319	0.01719	0.28681	0.31442	0.18165
2-week	0.82455	0.56920	0.00096	0.03669	0.07988	0.03854
3-week	0.30265	0.22157	0.02641	0.12179	0.20802	0.04209
4-week	0.64098	0.54608	0.17280	0.07073	0.11100	0.16524
5-week	0.21870	0.16368	0.48407	0.16655	0.20530	0.38474
6-week	0.27134	0.33037	0.96388	0.24121	0.23578	0.83047

CHAPTER 5

DISCUSSION & CONCLUSION

In this thesis, historical data were used to establish climatologies of flash and non-flash droughts to discern differences in basic characteristics. Furthermore, different types of drought were related to antecedent meteorological conditions, providing insight into the differences in onset between drought types. Here, the primary findings are re-examined in terms of the original research questions and existing flash drought literature.

The three research questions that guided this research (Chapter 1) asked:

1. How does intensification rate affect duration and frequency of drought events?
2. What meteorological conditions are associated with differences in drought intensification rate?
3. How do differences in drought intensification rate vary by region?

In the paragraphs that follow, each of these questions is addressed in turn.

This first question was answered in Section 4.2.1. Based on the results from establishing a flash and non-flash drought climatology for the CONUS, flash drought is most common in the South and Southwest but is also common in the Northwest and Plains. There is a hotspot in flash drought activity in northern Georgia and western South Carolina in the South region and west of the 100th meridian in the Plains and Southwest region. Overall, flash droughts are more common in every part of the United States except the west coast. In many areas, flash drought is around or above 70% more common than non-flash drought.

The second research question as it relates to duration and frequency of flash events was answered in Section 4.2.2. When the USDM flash and non-flash drought characteristics are broken down by region, differences between the regions emerged. The South and Southwest regions are more likely to have more frequent and longer flash drought events than non-flash drought events. The South and Southwest also are more likely to experience more frequent flash drought events when compared to the Plains and Northwest where the number of flash and non-flash drought events have a similar distribution.

The second and third (as it relates to meteorological variables) research questions were answered in Section 4.2.3. Once the PET, VPD, T_{min}, and T_{max} were analyzed between the regions and event types, some patterns emerged. Out of the four meteorological variables examined in this study, PET was the most reliable as an early warning sign of flash drought and temperature was not as reliable. This result makes sense as recent studies have suggested that flash droughts are driven by high atmospheric water demand and less so by temperature (Parker 2021). The maximum daily temperature is a better predictor of flash drought is closer to being significant than minimum temperature, which was far from being significant. However, daily T_{max} and T_{min} are not independent of one another. The higher daily T_{max}, the higher daily T_{min} will be as well. The insignificance of maximum and minimum temperature may be because these regions experience high temperatures more often during the study period (March through October) regardless of drought presence. A positive temperature anomaly does not necessarily need to be present for a flash drought to occur due to the anomaly being relative to the mean temperature. If the mean temperature is 40 degrees C and the anomaly is -10 for that drought, 30 degrees C is still very warm and would encourage drought if the correct precipitation deficit and atmospheric demand conditions were present. Therefore, VPD and PET were the most useful variables in predicting a flash drought occurrence.

The figures of the trend in mean anomalies from one to six weeks before an event for PET and VPD suggests that flash drought has anomalous PET and VPD five and six weeks before an event compared to the other two events while it was harder to distinguish between no drought event and non-flash drought event at five to six weeks. The differences in mean anomalies between flash and non-flash events for every region and most weeks are close to being significant with the conservative Bonferroni adjustment.

This study has found that a co-existence of flash droughts and non-flash droughts are most prevalent in the Northwest, Plains, Southwest, and South regions of the United States. Flash droughts are more common than non-flash droughts and are also more frequent and last longer than non-flash droughts, especially in the South and Southwest regions of the United States. This study supports previous research that has suggested a drought can form with any long-term precipitation deficit, but the conditions necessary for a flash drought include high temperatures and low humidity in addition to a precipitation deficit. That being said, low humidity and high potential evapotranspiration were better predictors than temperature in regions with less seasonality like the South and Southwest. Median values for PET, VPD, and T_{max} were the greatest for one to six weeks before flash drought. The same patterns can be seen with the mean anomalies, and most of the mean anomalies were statistically different than non-flash and no drought conditions.

One limitation of this study is the lack of precipitation data used to examine the meteorological drivers of flash drought. Precipitation data was left out because previous studies have suggested that a precipitation deficit is the main driver of all drought events. However, pairing each of the meteorological variables in this study with the severity of the precipitation deficit would be useful to determine what combination of severities in precipitation and the other variables would be most useful in predicting whether a drought event will be flash or non-flash. Another limitation of this study was the sample size of n=5 for both flash and non-flash drought for the regional analysis. This sample size value is subjective. To address this in the future, a sensitivity analysis should be done to determine the differences between the results for different sample sizes.

The main goal of all flash drought research is being able to accurately predict when and where a flash drought will occur with as much lead time as possible to give local governments and other stakeholders as much time as possible to minimize the economic consequences that often are associated with flash drought events. The lack of consensus about flash drought definition criteria has made this goal difficult to achieve. The two schools of thought are a definition based around intensification rate or a definition based on intensification rate coupled with duration. This study showed that flash droughts can have a mean length of up to 50 weeks in areas of flash drought prevalence. A definition based on rapid intensification, regardless of length, should be the standard because it is those events that have the potential to cause the most economic and environmental damage. This definition would encompass many droughts that have been categorized as “flash” based on a short-duration criterion (ranging from days to four months), but also would add flash droughts that last longer and are as equally if not more damaging than rapidly intensifying droughts that recover quickly.

This study suggests that in all areas except the far west coast, flash droughts are much more common than non-flash droughts. This may be because of the limitation in using the USDM, which only has four categories of drought with an additional category for abnormally dry conditions. The limited number of categories makes it difficult to break down flash drought into different rates of intensification, which limits the analysis that can be done regarding the meteorological drivers of rapid onset drought. That being said, other indices that have been used to define flash drought have the limitation of only focusing on certain variables. The benefit of the USDM is that it is an expert synthesis of a variety of variables and impacts to give a full-spectrum view of drought. The USDM should not be excluded from flash drought research but incorporating other indices into the evaluation of rapid onset drought can provide important detail and additional context that the USDM may not be able to provide.

Furthermore, in previous research that defined flash drought using the USDM, a drop in two categories in a period of four or six weeks was used. There is one recent study that required a drop in two categories in two weeks (Pendergrass et al. 2020). This may be a more useful definition if using the USDM. Due to the limited number of categories used by the USDM, a majority of drought events will see a drop in two categories in four weeks. The common general description for flash drought is a drought that rapidly intensifies causing significant damage compared to slower developing droughts. A drop in two categories in four weeks does not highlight the increased severity of these events, therefore, a more limited definition like the one used by Pendergrass et al. (2020) may be more reflective of the damaging nature of flash drought events. Even better may be a retrofit definition where flash drought is defined by being above a certain percentile of drought intensification or a recurrence interval. Either way, a flash drought definition should reflect the increased damage possible by these rapid onset droughts compared to conventional slower developing droughts.

The overarching goal of all flash drought research is to be able to predict a flash drought event with a good level of accuracy to minimize economic and environmental damage. This study has shown that there is a difference in PET and VPD before a flash event compared to a non-flash event. PET and VPD are also much more useful than temperature in predicting flash droughts. To get to the point of being able to predict flash droughts with some accuracy, much more work needs to be done. A flash drought early warning system should examine variables that result in high atmospheric water demand and rapid drying of the soil such as, relative humidity, vapor pressure deficit, potential evapotranspiration, and temperature. A useful next step would be to look at the variables together to determine if there are any combinations of meteorological variables like PET, VPD, and temperature values that result in a flash drought much more often than a non-flash drought. This same idea can be applied to drought indices as well. In addition to determining the best definition for flash drought, determining benchmarks and probabilities of a flash drought occurring given certain meteorological conditions is the next major step to being able to predict flash drought events.

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