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Meteorological conditions associated with the onset of flash drought in the Eastern United States

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ABSTRACT

Rapid onset droughts, termed "flash droughts", present a series of unique challenges for drought monitoring, forecasting, and mitigation. Due to the rapid onset and lack of early warning systems, stakeholders can be caught off-guard by flash droughts and suffer disproportionate impacts. Despite these impacts, little is known about the physical drivers of flash droughts. The purpose of this study is to determine antecedent meteorological conditions prior to the onset of flash drought in the Eastern United States. Emphasizing the agricultural impacts, flash droughts were defined as periods when the pentad-average 0–40 cm volumetric water content declines from at least the 40th percentile to below the 20th percentile in 4 pentads or less. Meteorological variables from 125 stations in the Eastern U.S. from March − October 1979 − 2010 were analyzed for their relationships with flash drought onset. Consistent with previous findings, flash drought was associated with decreased precipitation and humidity, increased solar radiation, and elevated temperatures. However logistic regression results suggest variables that accounted for surface moisture balance and/or atmospheric evaporative demand were more closely linked with the likelihood of flash drought than temperature and/or precipitation. Associated surface conditions are likely driven by ridging in the mid to upper level troposphere, which is shown to be more persistent leading up the flash droughts in the northern half of the study region. Our results elucidate the meteorological conditions immediately prior to the onset of one type or "flavor" of flash drought, defined by characteristic rapid intensification. Arguably, one could define flash drought with soil moisture thresholds varying from those used in this study and/or different time scales of soil moisture depletion. Therefore, we additionally argue that absences of both a standard flash drought definition and consistent precedent for identifying flash drought complicates monitoring and predicting these events.

1. Introduction

Drought is one of the most damaging and costly natural hazards in the United States because of the dependence on agriculture and the impact that drought has on water resources and ecosystems. For example, the 2011 drought caused an estimated $7.62 billion of agricultural losses and nearly $800 million in timber resources in Texas alone (Hoerling et al., 2013). Because of the risk drought poses, strategies have been developed worldwide, with particular foci on effective drought monitoring and communication (Hayes et al., 2011). One of the most comprehensive drought monitoring systems is the United States Drought Monitor (USDM), which was developed to track and communicate the severity and extent of drought across the United States (Svoboda et al., 2002). The USDM and other state-of-the-art drought monitoring systems assimilate information related to water resource availability, ecosystem health, and meteorological conditions from observations, satellite remote sensing, and models to generate a product that can be effective for a wide variety of end-users. However, despite the utility of comprehensive drought monitoring tools such as the USDM, they often have difficulty capturing rapidly evolving drought events commonly referred to as "flash droughts" (Svoboda et al., 2002; Senay et al., 2008; Otkin et al., 2013), first coined by Svoboda et al. (2002) .The rapid onset of flash droughts significantly reduces time available for impact mitigation, potentially resulting in greater adverse agricultural and societal effects than a slowly evolving drought event (Otkin et al., 2015). Concurrently, the physical drivers of flash droughts, common to regions of the United States east of the Rocky Mountains (hereafter regarded as the Eastern United States), are not well understood (Mo and Lettenmaier 2016). This is in contrast to conventional droughts such as the 2011 Texas event and drought events of the 1930s and 1950s, as the causes of these droughts are known to be remote factors such as sea-surface temperature (SST) anomalies

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augmented by land-atmosphere interactions and soil moisture desiccation (Schubert et al., 2004; Fernando et al., 2016). The primary consequence of the knowledge gap of the drivers of and meteorological conditions that lead to flash drought is a lack of effective monitoring and forecasting infrastructure. Indeed, the 2012 Great Plains flash drought arrived without early warning from seasonal climate forecast models and operational drought monitoring systems (Hoerling et al., 2014; Kam et al., 2014). The economic losses directly attributed to the 2012 drought in the United States exceeded $12 billion (Hoerling et al., 2014).

The frequency with which flash droughts occur in the Eastern United States (Mo and Lettenmaier 2015) combined with the significant lack of knowledge and capability to predict and monitor flash drought underscore the need for investigation of the meteorological conditions that lead to flash drought onset. One consistent theme amid the studies examining flash droughts in the United States is the importance of soil moisture observations and evapotranspiration for flash drought monitoring and forecasting (Otkin et al., 2014; Ford et al., 2015). Additionally it is known that inception of flash drought in the Eastern United States occurs with rapid declines in soil moisture availability, attributed to decreased precipitation and amplified by increased air temperature and elevated evaporative demand (Otkin et al., 2013; Mo and Lettenmaier 2015). With this in mind the purpose of this project is to determine both the antecedent meteorological conditions most strongly associated with flash drought occurrence and the time-scale at which these connections occur. The scope of this analysis is climatological, such that we do not focus on one or two particular flash drought events, but identify flash droughts over a 32-year time period and describe the atmospheric conditions associated with a station's flash drought climatology.

2. Material and methods

2.1. Meteorological observations

Hourly observations of temperature, dew point temperature, station pressure, relative humidity, precipitation, and wind speed between 1979 and 2010 were obtained from 125 "first order" weather stations across the Eastern United States (Fig. 1), defined as all states east of the Rocky Mountains or approximately 105°W longitude. The stations were selected as a compromise between 1) spanning the geographic entirety of the Eastern United States, 2) working with nearly serially-complete, high quality observations, and 3) inclusion in the National Solar Radiation Database program (see below). Hourly observations were assigned to the nearest rounded hour and partitioned into the traditional eight 3-h time blocks (0000–0300 LST, 0300–0600 LST, etc.). Daily maximum temperature (T_{MAX}, °C), mean 2-m wind speed (*Wspd*, ms^{-1}), mean relative humidity (*RH*, %), total solar radiation (*Srad*, Wm^{-2}), and total precipitation (*Precip*, mm) were computed from the 3-h average or total values; however, they were only considered if at least one valid hourly observation was included in each 3-h block. If one of the 3-h blocks was missing for a variable, the variable was not computed for that day. In this situation, all other variables were computed for that particular day, given all 8, 3-h blocks were valid. T_{MAX} was included for each 3-h block as the maximum hourly temperature recorded in that block. Therefore, daily T_{MAX} represents the actual maximum hourly temperature value for that day. A station was considered for the analysis if less than 10% of daily observations were missing. Additionally, we computed daily average vapor pressure deficit (*VPD*, mb) as the difference between the saturation vapor pressure at the daily maximum and minimum air temperatures (e_s) and the actual vapor pressure (e_a). The former is calculated such that:

$$e_s = \frac{e_{Tmax} + e_{Tmin}}{2}$$

where

$$e_T = 0.6108e^{\left(17.67T/T+237.3\right)},$$

and the latter is computed using the empirical relationship of Bolton (1980) from daily average dew point temperature (T_d, °C):

$$e_a = 6.112\exp\left(\frac{17.67T_d}{T_d + 243.5}\right).$$

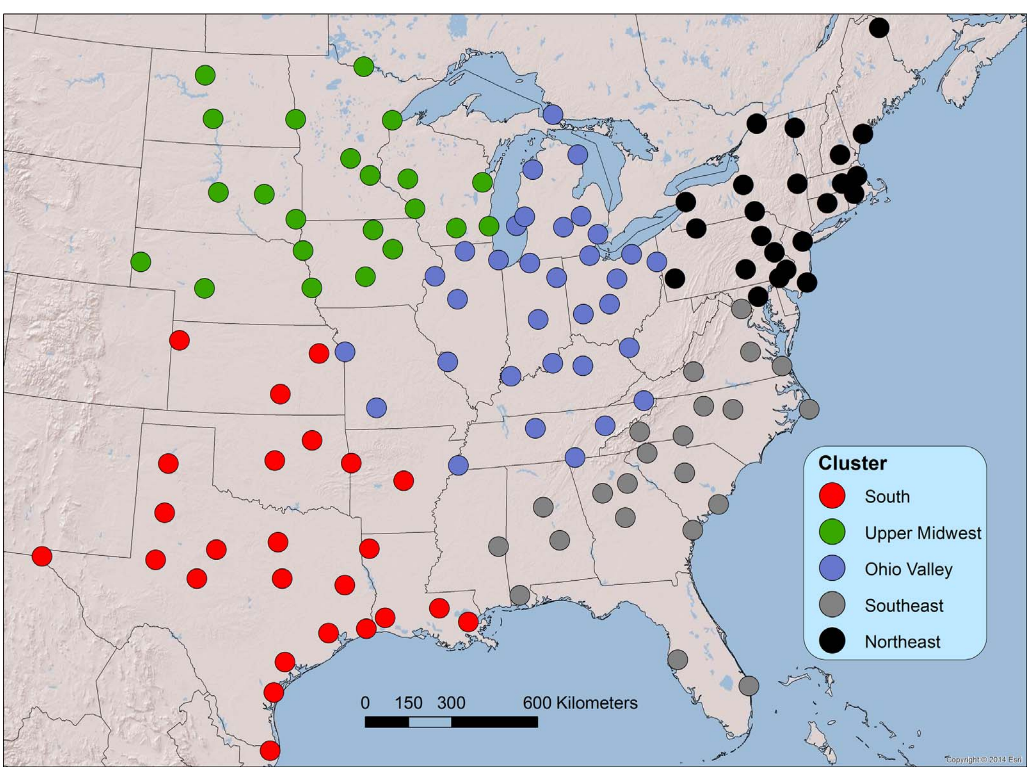

Fig. 1. Map of first-order weather stations, from which meteorological conditions are composited. The stations are colored based on their respective cluster (clusters based on National Centers for Environmental Information (NCEI) climatic regions, as in Karl and Koss (1984)).