

The flash droughts across the south-central United States in 2022: Drivers, predictability, and impacts

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ABSTRACT

A rare subseasonal-to-seasonal phenomenon – two consecutive flash drought events interrupted by a period of recovery – occurred across eastern Oklahoma, Arkansas, and southern Missouri, spanning the summer and early fall of 2022. These flash drought events (the first in June–July, the second in August–September) led to severe (D2) and extreme (D3) drought conditions via the United States Drought Monitor across much of the region following the first period of rapid drought intensification, and extreme (D3) and exceptional (D4) drought conditions by the end of the second event. A notable driver of both flash drought events included a persistent upper-level ridge either centered over or shifted west and upstream of the flash drought region, leading to broad-scale subsidence and reduced mid-level moisture which acted to limit precipitation development and increase evaporative demand. In addition, several heatwave events developed during the warm season in 2022 and either (1) acted to drive flash drought development via increased evaporative demand or (2) were enhanced by land surface desiccation and land-atmosphere feedbacks following rapid drought intensification. Furthermore, S2S composite forecasts predicted drought development for both events. However, only 20% of the ensembles predicted rapid drought development associated with flash drought for the first event and 16% of the ensembles predicted rapid drought development during the second event. This result highlights a key challenge in S2S prediction of rapidly developing drought conditions versus that of more conventional and slower drought development. The ensembles that did predict rapid drought intensification were associated with the forecasting of positive 500 hPa geopotential height anomalies over the south-central United States (first event) or an amplified wave pattern centered over the west-central United States (second event). Lastly, the compounding effects of two flash droughts in a single warm season led to substantial impacts on agricultural, environmental, and hydrologic sectors across the region.

1. Introduction

Flash droughts are characterized by the rapid development of drought conditions and are distinct from conventional, slowly developing droughts (Otkin et al., 2018). While a lack of precipitation is fundamental for all types of drought development, flash drought is driven by a combination of above-average evaporative demand coupled with precipitation deficits (Christian and Coauthors, 2024). Further, the rapid intensification of drought conditions can lead to wide-ranging

impacts, including agricultural yield loss, vegetation health decline, reduced water resources, increased wildfire risk, and enhance risk of heatwave development (Jin et al., 2019; Christian et al., 2020; Hoell and Coauthors, 2020; Otkin and Coauthors, 2022). Two of the most prominent flash drought events within the United States include the 2012 flash drought across the central United States and the 2017 flash drought in the Northern Great Plains of the United States (Otkin and Coauthors, 2016; He et al., 2019; Basara et al., 2019; Hoell and Coauthors, 2020). Overall, these individual events led to economic losses in excess of \$30

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billion and \$3 billion respectively (NCEI 2024).

A rare sequence of consecutive flash drought events occurred in the south-central United States during the warm season of 2022. During early June, drought conditions were absent across eastern Oklahoma, Arkansas, and southern Missouri via the United States Drought Monitor (USDM; Supplementary Fig. 1a). Further, 12 cm of rainfall fell across the region during a three-week span in late May and early June (Fig. 1a). However, environmental conditions rapidly deteriorated, driven by an extended period of minimal precipitation and enhanced evaporation demand associated with above-average temperatures (Figs. 1a and 2, Supplementary Fig. 2a). The combination of these anomalous conditions led to flash drought over a 30-day span throughout June and early July (the first flash drought event, FD1), collectively demonstrated by a rapid increase in evaporative stress on the environment (shown via the standardized evaporative stress ratio metric; SESR; Figures, 1a,b). This period of rapid drought development was also indicated by the flash drought blend from the National Drought Mitigation Center (NDMC; Fig. 1d). Additionally, USDM drought categories reached severe drought (D2) and extreme drought (D3) by late July following drought persistence after the period of rapid drought intensification (Supplementary Fig. 1b). The region experienced a period of precipitation from late July to mid-August, reducing the evaporative stress to return to near-normal conditions by mid-August and contributing to notable improvement in USDM categories by early September (Supplementary Figs. 1c and 2c). Despite this recovery, a second flash drought event (FD2) occurred over the same region within the south-central United States in late August and September (Fig. 1a–c,e), leading to D3 and exceptional drought (D4) conditions over eastern Oklahoma, southeastern Kansas, central Arkansas, and southwestern Missouri (Supplementary Fig. 1d).

Individual flash drought events are regarded as a relatively rare phenomena given their unusually rapid rate of drought development or intensification and are considered a subset of drought (Otkin et al., 2018). Although the south-central United States is located within a hotspot for flash drought development (Chen et al., 2019; Otkin and Coauthors, 2021), flash drought events typically occur only two out of every five years in this region (Christian et al., 2019; Osman et al., 2021). The south-central United States is also associated with large precipitation variability (Ting and Wang 1997; Ruiz-Barradas and Nigam 2005; Flanagan et al., 2017) and is known to have rapid transitions between pluvial and drought conditions, and vice versa (Christian et al., 2015; Dong and Coauthors, 2011). For example, this region experienced a flash drought-flash recovery sequence during the fall of 2015 with cascading impacts associated with the rapid drought intensification and period of excessive precipitation (Otkin et al., 2019). During the prior 42 years (1980–2021), the average chance of two flash droughts occurring across the south-central United States (the domain encompassing eastern Oklahoma, Arkansas, and southern Missouri) during the same year was 4.3% (Supplementary Fig. 3). This percentage equates to a return period for a dual flash drought event approximately once out of every 25 years across the region. As such, while the south-central United States is familiar with rapid subseasonal transitions between droughts and pluvials, the flash drought-recovery-flash drought sequence during summer and fall of 2022 was a particularly unique and rare set of events.

While both flash droughts occurred in the same growing season over the same region, each event had distinct drivers and features in subseasonal-to-seasonal (S2S) predictability. Further, the sequence of two flash droughts events across the south-central United States led to compounding impacts on heatwave development, rapid vegetative health decline, agricultural losses, increased risk for wildfire occurrence, and reduced streamflow. This study highlights (1) the atmospheric drivers that led to the development of the dual flash drought events across the south-central United States, (2) the timing and relationship between heatwave and flash drought development, (3) the S2S predictability of both flash droughts, and (4) the wide-ranging impacts resulting from the unique sequence of two flash droughts in a single

warm season.

2. Methods

2.1. Domain

The study domain is focused over eastern Oklahoma, southeastern Kansas, Arkansas, and southern Missouri with bounded latitudes and longitudes of 33.75°N, 38.75°N, 96.25°W and 89.25°W and encapsulated the approximate area where both flash drought events occurred during the warm season of 2022 (Fig. 1b–c, Supplementary Fig. 4). In addition, time series shown in this study are domain-averaged quantities using the latitudinal and longitudinal bounds previously listed.

2.2. Data

Data from the European Center for Medium-Range Weather Forecasts (ECMWF) fifth reanalysis (ERA5; Hersbach and Coauthors, 2020) was used for the land surface variables and atmospheric variables in the analysis at a spatial resolution of 0.25°, spanning the period 1980–2022. ERA5 has been used in previous studies to effectively capture flash drought (Christian et al., 2021; Mahto and Mishra 2023; Mukherjee and Mishra 2022; Parker et al., 2021). A climatological period from 1980 to 2021 was utilized with standardized variables detrended prior to standardization.

The enhanced vegetation index (EVI; Huete et al., 2002) from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the NASA Aqua and Terra satellites was used to evaluate vegetative conditions during the flash drought (and recovery) events. EVI has previously been shown to identify drought, be sensitive to rapidly developing drought conditions, and has been used to quantify land surface desiccation during flash drought (Bajgain et al., 2015; Christian et al., 2020; Wagle and Coauthors, 2014; Zhou and Coauthors, 2017). The method presented in Chen et al. (2004) was utilized to smooth the EVI time series at each grid point while preserving the seasonality of spectral retrievals. A summary of the multi-step process using the Savitzky-Golay filter for smoothing is provided in Christian et al. (2022). After the EVI time-series was smoothed it was then standardized at each grid point using the period spanning 2003–2021. The spatial resolution of the EVI used in the analysis was 0.05°.

Weekly USDM data (Svoboda and Coauthors, 2002) was used to assess the change and severity of drought conditions during the two flash drought events. The USDM provides weekly composite drought analysis using a convergence of evidence approach that incorporates an objective blend of several drought indicators and indices as well as peer review and reports from local drought experts. The USDM is a commonly used tool to evaluate drought evolution and magnitude during a flash drought event (Basara et al., 2019; Christian et al., 2022; Ford et al., 2015; Otkin et al., 2013). As part of the weekly analysis, the USDM authors have recently incorporated a standardized weekly flash drought “objective blend” to help identify and classify both the development of a flash drought event or the rapid intensification of existing drought events (National Drought Mitigation Center 2023). The weighted inputs into the flash drought blend include the 1-month Standardized Precipitation Evapotranspiration Index (SPEI; 25%), 0–40 cm NOAH soil moisture (25%), 2-week Evaporative Demand Drought Index (EDDI; 20%), 4-week Evaporative Stress Index (ESI; 20%), and the Quick Drought Response Index (QuickDRI; 10%).

To explore the predictability of both flash drought events, soil moisture (0–20 cm) and 500 hPa geopotential height were used from hindcasts of the European Center for Medium-Range Forecasts (ECMWF) S2S real-time model, used as part of the S2S Project Database (Vitart and Coauthors, 2017). The ECMWF model has 51 ensemble members with 46-day (soil moisture) and 47-day (500 hPa geopotential height) forecasts at a 1.5° spatial resolution. Forecasts initializations were selected for the dates on or just prior to the start of rapid drought intensification.

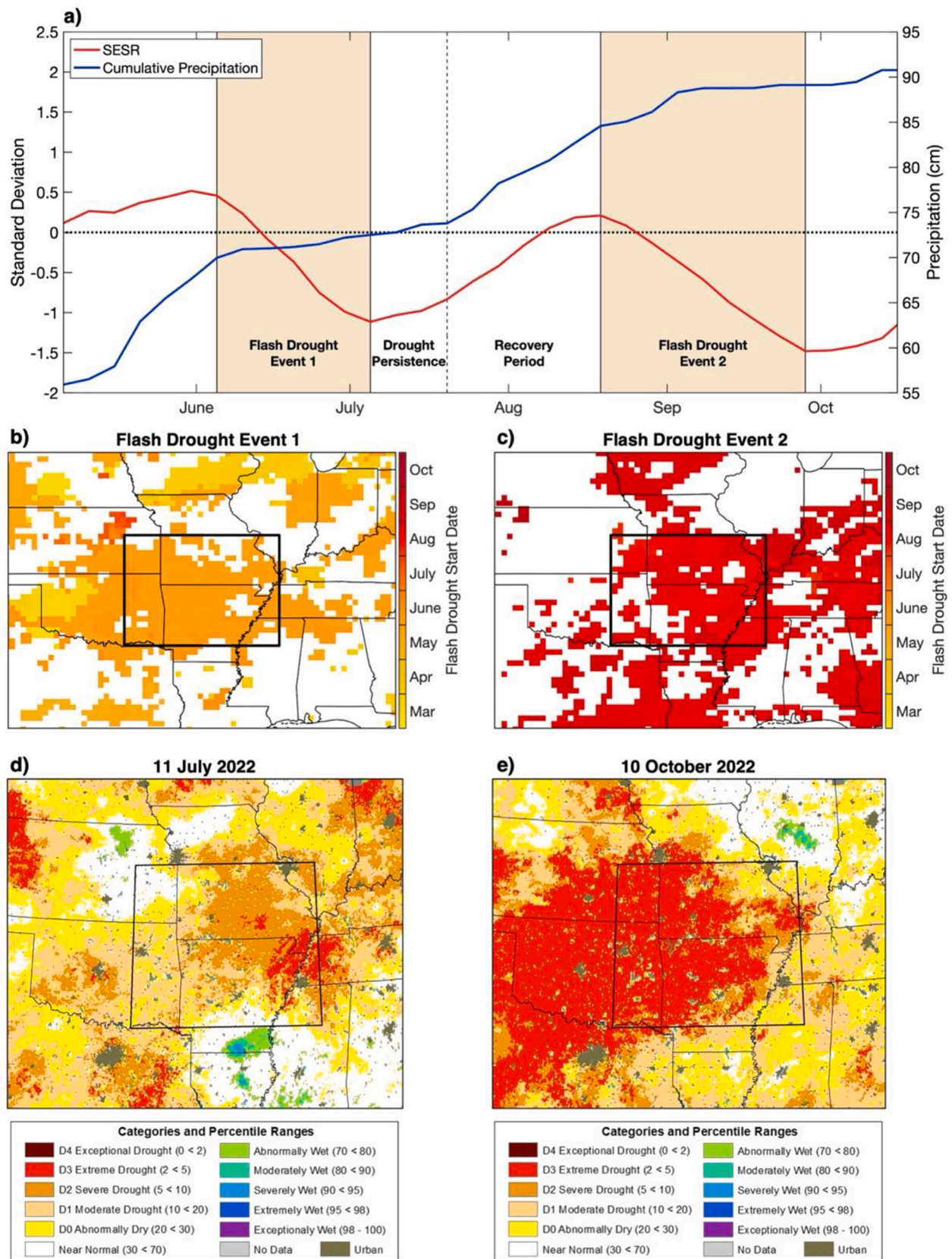


Fig. 1. a) Domain-averaged SESR and cumulative precipitation (beginning January 1, 2022) from ERA5, b) the date of when flash drought began for the first flash drought event (June–July), c) the date of when flash drought began for the second flash drought event (August–September), and d-e) the NDMC flash drought objective blend on 11 July and 10 October 2022, respectively. The domain for areal-averaged variables in a) is shown in b-e). The tan shaded region in a) indicates median flash drought timing for grid points located in the domain. Details for the flash drought identification process are provided in Section 2.3.1, and details for the NDMC flash drought objective blend are provided in Section 2.2.

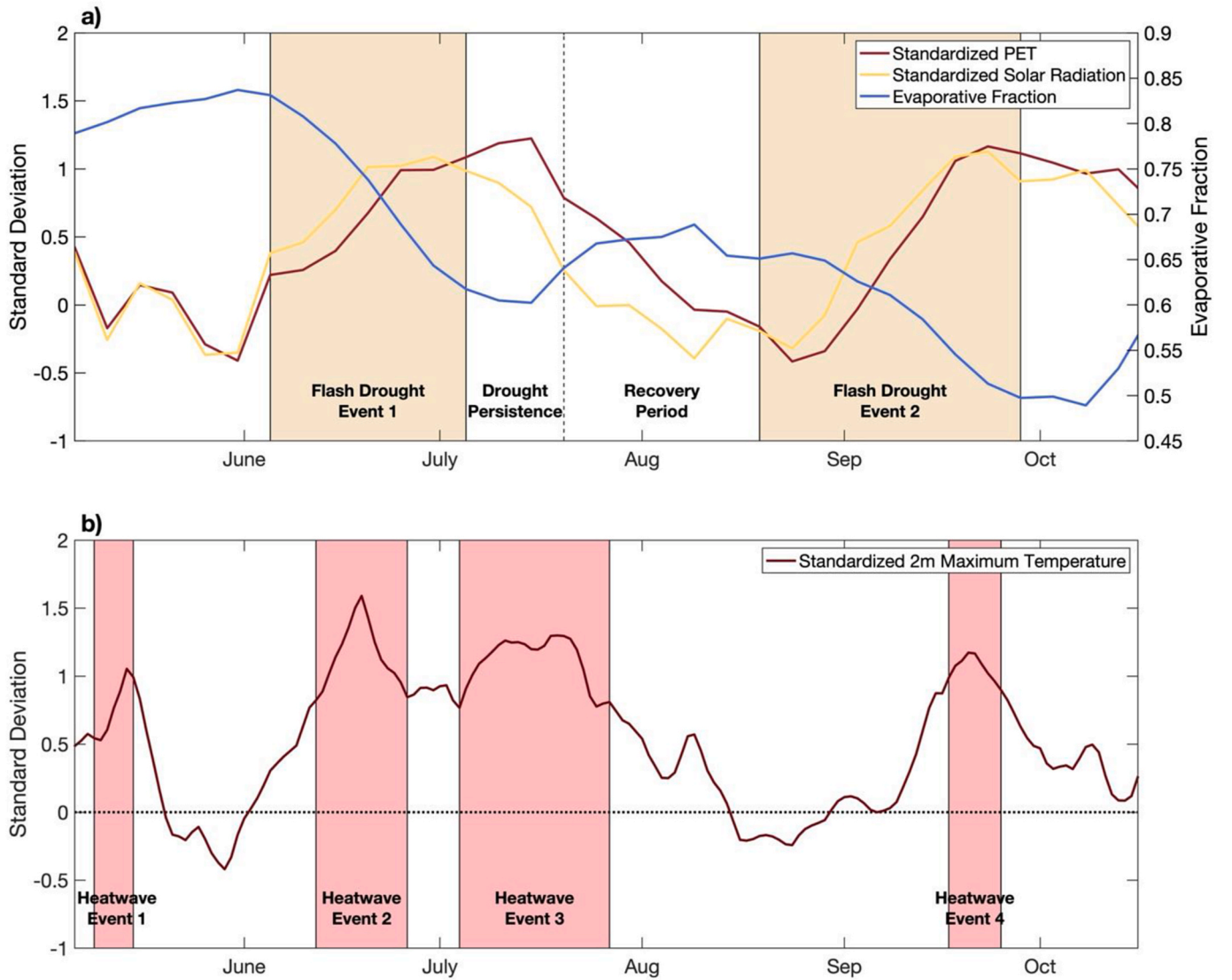


Fig. 2. a) Domain-averaged standardized PET, standardized solar radiation, and evaporative fraction and b) domain-averaged standardized 2-m temperature from ERA5. The domain for areal-averaged variables is shown in Fig. 1b–c. The tan shaded region in a) indicates median flash drought timing and the red shaded region in b) indicates heatwave timing for grid points located in the domain. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

These initialization dates included June 2, 2022 for the first flash drought and August 18, 2022 for the second flash drought. Soil moisture and 500 hPa geopotential height from the ECMWF S2S models were standardized using the lead time dependent climatologies from the 11 member hindcast ensembles between 2002 and 2021. Statistical significance was computed via bootstrapping with 5 000 iterations at the 99% confidence level. Each sample in the bootstrap was composited using the same number of ensembles that identified (or did not identify) flash drought.

2.3. Definitions

2.3.1. Flash drought identification

The spatial and temporal evolution of flash drought was captured using the evaporative stress ratio (ESR; Christian et al., 2019). ESR was derived from ERA5 by calculating the daily ratio of evapotranspiration and potential evapotranspiration (Equation (1)). Here, potential evapotranspiration was quantified using the Food and Agriculture Organization Penman-Monteith equation (Allen et al., 1998). Mean pentad values of ESR were then computed and standardized to calculate the

standardized ESR (SESR, Equation (2)).

$$ESR = \frac{ET}{PET} \quad (1)$$

$$SESR_{gp} = \frac{ESR_{gp} - \overline{ESR}_{gp}}{\sigma_{ESR_{gp}}} \quad (2)$$

$SESR_{gp}$ (referred to herein as just SESR) is the z-score of ESR at a specific grid point (g) for a specific pentad p, $\overline{ESR}_{gp}$ is the mean ESR at a specific grid point (g) for a specific pentad p for the years between 1980 and 2021, and σ_{ESR} is the standard deviation of ESR at a specific grid point (g) for a specific pentad p for the years between 1980 and 2021.

Following guidance of Savitzky-Golay filtering to remote sensing observations (Chen et al., 2004) and previous flash drought studies (Christian et al., 2022; Lowman et al., 2023), the Savitzky-Golay filtering method was applied to each grid point to reduce the pentad-to-pentad variability of SESR and better capture subseasonal-scale development of flash drought. Here, $d = 4$ was used for the degree of polynomial and $m = 10$ was used as the half-width of the smoothing window (full window length of 21 pentads; Christian

et al., 2022; Lowman et al., 2023).

Following the calculation of SESR and the Savitzky–Golay filter, the temporal change in SESR was calculated (Equation (3)) and standardized (Equation (4)).

$$\Delta\text{SESR}_{gp} = \text{SESR}_{gp} - \text{SESR}_{g(p-1)} \quad (3)$$

$$(\Delta\text{SESR}_{gp})_z = \frac{\Delta\text{SESR}_{gp} - \overline{\Delta\text{SESR}_{gp}}}{\sigma_{\Delta\text{SESR}_{gp}}} \quad (4)$$

$(\Delta\text{SESR}_{gp})_z$ (referred to herein as just ΔSESR) is the z-score of the change in SESR from one pentad to another pentad at a specific grid point (g) for a specific pentad p, $\overline{\Delta\text{SESR}}$ is the mean change in SESR values at a specific grid point (g) for a specific pentad p for the years between 1980 and 2021, and $\sigma_{\Delta\text{SESR}}$ is the standard deviation of SESR changes at a specific grid point (g) for a specific pentad p for the years between 1980 and 2021.

Flash drought was identified using a framework previously established in Christian et al. (2019) and modified in Christian and Coauthors (2023) and Lowman et al. (2023). The methodology uses three criteria, with two focusing on the impacts of drought and one emphasizing the rapid drought intensification. These criteria are.

1. ΔSESR must be at or below the 25th percentile of ΔSESR values.
2. A minimum length of five pentad changes in SESR, equivalent to a length of six pentads (30 days).
3. A final SESR value below the 20th percentile of SESR values.

Percentiles for criterion 1 were obtained from the distribution of ΔSESR and percentiles for criterion 3 were taken from the distribution of SESR at each grid point and specific pentads for the years between 1980 and 2021 in the ERA5 dataset. The start date of flash drought is defined as the first pentad in which criterion 1 is satisfied.

Because the ECMWF hindcasts do not provide the variables necessary to compute SESR, soil moisture (0–20 cm) was used to assess the predictive skill of the models. To verify that soil moisture can also be used to identify the two flash drought events across the south-central United States in 2022, ERA5 soil moisture (7–28 cm) was used in the flash drought identification methodology described above. Overall, soil moisture used in conjunction with the methodology was able to identify two flash droughts during the south-central United States with the timing and spatial distribution of flash drought very similar to that depicted by SESR (Fig. 1b–c, Supplementary Fig. 5).

To identify flash drought in the ECMWF hindcasts, soil moisture was averaged into pentads, with the dates aligned with the pentad dates of SESR. As such, the first pentad date of soil moisture in the S2S models was June 5, 2022 for the first flash drought event and 19 August for the second flash drought event, resulting in 8 lead time pentads and 9 lead time pentads, respectively. Lastly, soil moisture was averaged across the study domain using grid points that fell within the domain boundaries (33.75°N–38.75°N and 96.25°W–89.25°W).

Flash drought was identified in the S2S models using more lenient criteria. These criteria were given as.

1. Change in soil moisture must be at or below the 40th percentile.
2. A minimum length of three pentad changes in soil moisture, equivalent to a length of four pentads (20 days).
3. A final soil moisture value below the 20th percentile of soil moisture values.

Percentiles for criterion 1 were obtained from the distribution of the change in domain-averaged soil moisture and percentiles for criterion 3 were taken from the distribution of domain-averaged soil moisture at specific pentads for the years and ensembles between 2002 and 2021 in the ECMWF S2S hindcast models.

Criterion 1 was changed from the 25th to 40th percentile due to areal

size of flash drought identification and inability to smooth the time series prior to identification. Because grid points were averaged across the study domain prior to flash drought identification, the rate of soil moisture decline will be reduced compared to individual grid point identification. The differences in the spatial scales of grid points between the S2S models (1.5°) and ERA5 (0.25°) also muted the rate of rapid drought intensification. Several model grid cells with centers that were within the study domain boundaries represented large areas that also fell outside of the study domain. Further, the short time period of soil moisture (8 or 9 pentads depending on the flash drought event) from the ECMWF hindcasts restricted smoothing of the soil moisture time series. Using smoothing techniques on S2S timescales, such as the Savitzky–Golay filtering technique used on SESR, acts to smooth short periods of moderation due to precipitation while preserving rapid changes in an index. This process allows rapid drought development to be identified using a stricter criterion (e.g., 25th percentile). Due to a lack of smoothing on the soil moisture time series, this also required a change of criterion 1 from the 25th percentile to 40th percentile. Similarly, the short time period of soil moisture in the ECMWF forecasts required a reduction in criterion 2 with a minimum length of flash drought from six pentads (30 days) to four pentads (20 days). These changes supported the goal of finding evidence of flash drought development in the S2S models.

2.3.2. Heatwave identification

Heatwaves and flash droughts are intrinsically linked through the drivers that lead to the development of both type of events. A key element of flash drought development is elevated evaporative demand due to above-average temperatures, and periods of rapid drought intensification are often found to coincide with excessive heat (Wang et al., 2023). Conversely, flash drought events can rapidly desiccate the land surface and lead to land-atmosphere interactions that promote heatwave development (Christian et al., 2020). As such, we identify and evaluate the timing and intensity of heatwaves with respect to the two flash drought events across the south-central United States during the warm season 2022.

Heatwave events were identified by using a 7-day running window of daily maximum 2-m air temperature averaged across the domain. Temperature was detrended and standardized prior to analysis. In previous studies, heatwaves have been defined either by percentile or via relative thresholds (Smith et al., 2013). Following this approach, heatwave events were identified using the 90th percentile (Anderson and Bell 2011; Hattis et al., 2012; Steadman 1984).

To be classified as a heatwave in the dataset, three criteria were required.

1. Daily maximum 2-m temperature must be at or above the 90th percentile.
2. A minimum length of 3 consecutive days of criterion 1 was required.
3. The end of the heatwave event occurred when the daily maximum 2-m temperature was below the 90th percentile for more than 3 consecutive days.

3. Results and discussion

3.1. Drivers

3.1.1. Atmospheric composites

An important synoptic-scale feature of flash drought development is the presence of a mid-tropospheric atmospheric ridge that simultaneously limits precipitation and increases evaporative demand. Several studies have identified strong ridging during drought development and maintenance (Namias 1983; Trenberth and Arkin 1988; Trenberth and Branstator 1992; Hoerling et al., 2014) and, in particular, during flash drought occurrence (Christian et al., 2020; Fu and Wang 2022).

During the first flash drought event (FD1; 5 June – 5 July), anomalous

500 hPa geopotential heights developed and persisted directly over the study domain, yielding subsidence and increased evaporative demand (Figs. 2, 3a and 4a). Throughout the drought persistence stage (6 July – 20 July) following FD1, the largest positive geopotential height anomalies shifted westward and were centered across the west-central United States (Fig. 3b). However, this shift continued to support subsidence and increased evaporative demand (Figs. 2 and 4b). This mid-tropospheric pattern was also present during FD2 (19 August – 28 September; Fig. 3d), promoting strong subsidence during this period as well (Fig. 4d). In all three temporal windows during which flash drought occurred or drought conditions persisted, the anomalous ridging limited precipitation over the region, enhanced prolonged periods of positive temperature anomalies and decreased atmospheric water vapor (Figs. 1a and 5a,b,d, Supplementary Figs. 2a,b,d). Conversely, an additional shift in the ridge was noted during the recovery period from late July to mid-August, which promoted zonal flow over the domain and a more active synoptic pattern (Fig. 3c). As a result, synoptic subsidence weakened, atmospheric water vapor increased, and increased precipitation occurred throughout most of the domain during this period (Figs. 1a, 4c and 5c, Supplementary Fig. 2c).

3.1.2. Heatwaves

While precipitation deficits are the first-order driver of flash drought, anomalous, increased temperatures exacerbate atmospheric demand and promote flash drought development (Ford and Labosier 2017; Otkin et al., 2013, Otkin et al., 2018). Given the unique nature of two flash drought events within one calendar year (i.e., 2022), an intricate relationship between the timing, intensity, and duration of heatwave events coupled with the flash droughts occurred. For example, while temperatures were near-normal in late May (Figs. 1a and 6a), a shorter-duration (e.g., 7 days) heatwave event occurred prior to the onset of FD1 in early to mid-May (Fig. 7). While this precursor heatwave event was shorter in duration, the magnitude was strong, ranging greater than 6 °C above normal (Fig. 7). Because above-average soil moisture and temperatures (associated with near-normal solar

radiation) were present during early May, the environment was neither water-limited nor energy-limited and contributed to an enhanced green-up of vegetation prior to FD1 (Fig. 1a, 2 and 8). The buildup of vegetation leads to significant increases in evapotranspiration and a rapid depletion of soil moisture, increasing the risk of flash drought development. The role of early or enhanced vegetative green-up in flash drought has been noted in prior events, such as the flash drought across the central United States in 2012 (Christian et al., 2022; Wolf and Co-authors, 2016).

A strong heatwave occurred during the middle of FD1 with the heatwave event beginning on 12 June, lasting for 15 days, and exceeding a severity index of 60 (Fig. 7) and was exacerbated by synoptic scale dynamics whereby the dominant upper-level ridge centered over the study domain drove increased subsidence across the region and further enhanced the extreme surface temperatures (Figs. 3a, 4a and 6b). As such, the heatwave temperatures between 12 June – 26 June enhanced the overall evaporative demand (Fig. 2) and promoted the rapid development of drought conditions.

During the drought persistence stage (6 July – 20 July) following FD1, mid-tropospheric ridging persisted and contributed to the onset of the third heatwave event spanning 4 July – 27 July 27 (Figs. 3b, 6c and 7). However, heatwave development was also supplemented by positive land-atmosphere feedbacks due to land surface desiccation associated with FD1 whereby root zone soil moisture was significantly depleted (Fig. 8). In the partitioning of surface fluxes, evaporative fraction was drastically reduced indicating a rapid decrease in latent heat flux relative to sensible heat flux (Fig. 2). Thus, evaporative cooling at the land surface was limited, promoting and amplifying heatwave development during this timeframe. The third heatwave event across the study domain had the highest severity index compared to all the 2022 heatwave events (Fig. 7), potentially due to the compounding drivers of atmospheric forcing and land-surface feedback (Domeisen and Co-authors, 2023). This heatwave event lasted for 24 days with an average temperature anomaly of 3.6 °C.

The beginning of the recovery period coincided with the end of the

Daily 500hPa Geopotential Heights

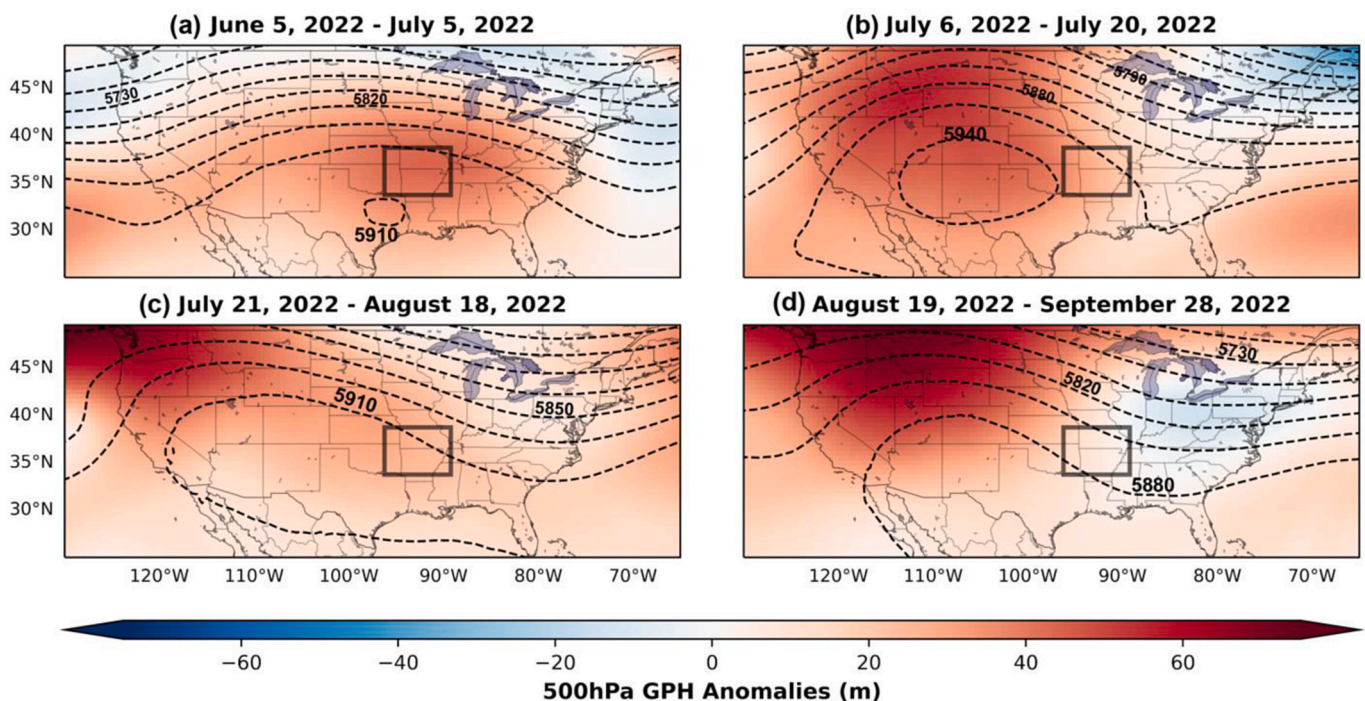


Fig. 3. 500 hPa geopotential heights (m; black dashed lines) and anomalies (m; shaded) during a) the first flash drought event, b) the drought persistence period, c) the recovery period, and d) the second flash drought event.

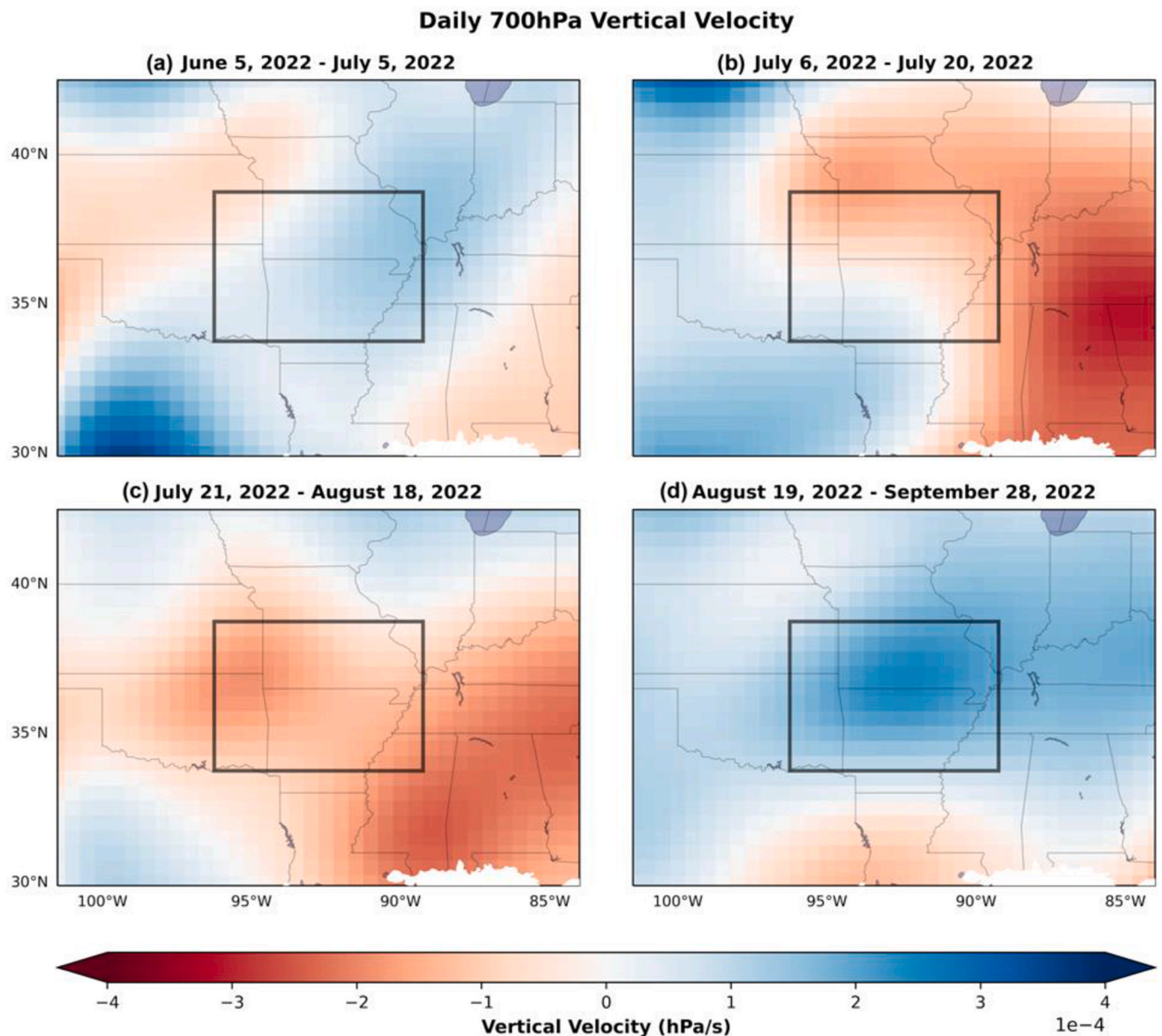


Fig. 4. 700 hPa vertical velocity (hPa/s) during a) the first flash drought event, b) the drought persistence period, c) the recovery period, and d) the second flash drought event.

third heatwave event. The axis of the mid-tropospheric ridge shifted further west of the spatial study domain and surface temperatures across the south-central United States slowly transitioned back to near-normal (Figs. 1a, 3c and 6d). During the recovery period, no additional heatwave events developed, low-level atmospheric ascent increased, and precipitation occurred (Figs. 1a and 4c). The absence of extreme temperatures along with increased precipitation during this recovery period yielded increased soil moisture and standardized EVI values along with a reduction in drought intensity according to the USDM from severe and extreme (D2-D3) drought conditions to abnormally dry (D0) and moderate (D1) drought conditions across much of the region (Fig. 8 and Supplementary Fig. 1).

FD2 began on August 19, but the fourth heatwave event within the study region did not occur until the end of FD2 (Fig. 7). While the heatwave was of high magnitude (maximum daily temperature anomaly of 6.2 °C), it was also shorter in duration compared to heatwaves two and three (9 days; Fig. 7). Across much of the study region, surface maximum temperature anomalies were at or above 4 °C (Fig. 6e). At this

time, the highest 500 hPa geopotential height anomalies shifted eastward after the recovery period which placed the study region slightly downstream of the strong ridge and increased subsidence (Figs. 3d and 4d). This resulted in drying of the lower troposphere (Fig. 5d), above-average surface temperatures (Fig. 6e), and precipitation deficits (Fig. 1a). Further, evaporative fraction was relatively low with above-average evaporative demand (Fig. 2). As such, the fourth event heatwave was driven by the overlying atmospheric conditions and assisted in driving FD2 towards the end of rapid drought development via land-atmospheric interactions. Lastly, above-average temperatures remained and persisted following the period of rapid drought development in FD2 (Fig. 6f).

3.2. Predictability

Improved S2S predictability is a critical focus area within the topic of flash drought (Pendergrass and Coauthors, 2020); however, limited research has quantified the S2S predictive skill of flash droughts. A study

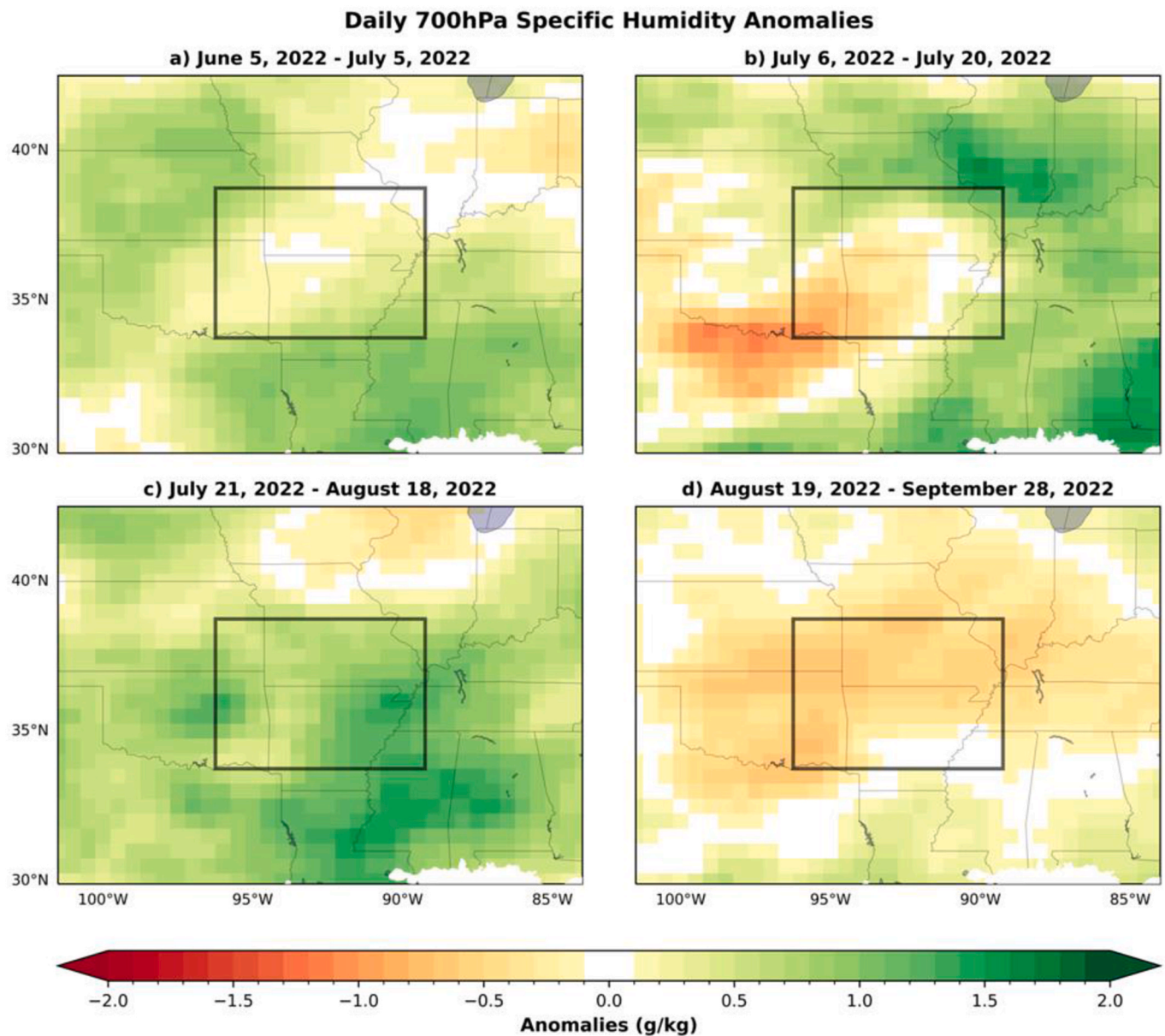


Fig. 5. 700 hPa specific humidity anomalies (g/kg) during a) the first flash drought event, b) the drought persistence period, c) the recovery period, and d) the second flash drought event.

by DeAngelis et al. (2020) analyzed the prediction skill of the 2012 central United States flash drought using SubX models (Pegion and Coauthors, 2019). Model skill was assessed by using anomaly correlations to determine how well the models were able to predict key variables (i.e., precipitation and temperature) during flash drought development. It was found that S2S models may provide useful prediction skill of precipitation and temperature in the first two forecast weeks but have limited skill at 3–4 week lead times. In particular, S2S models struggle to capture to rapid drought intensification associated with flash drought. In Ma and Yuan (2023), predictive skill of S2S models were evaluated using flash drought events during a 22-year period (1999–2020) over China. It was found that the models can predict approximately 20% of the observed flash drought events at a 1-week lead time. However, this predictability falls to 4% at a 3-week lead time, highlighting the challenges of predicting flash drought on S2S timescales. Beyond these two studies, additional studies have also focused on the role of teleconnections on flash drought development (Nguyen et al., 2021; Schubert et al., 2021).

The two flash droughts across the south-central United States provide an opportunity to investigate the predictive skill of S2S models. Specifically, we seek to understand if S2S models have any skill in capturing the rapid drought intensification associated with flash drought using an objective identification methodology. Here, we assess S2S predictability of flash drought using models initialized at the beginning of flash drought onset (e.g., when rapid drought intensification begins) and determining which ensemble members predict full flash drought event development over the following six weeks of forecasts. Analysis of the 51 ensemble members from the ECMWF S2S models show that approximately 20% of the ensembles ($n = 10$) were able to capture flash drought during FD1 spanning June and early July while approximately 16% of the ensembles ($n = 8$) captured FD2 in August and September (Fig. 9). In the days leading up to the onset of FD1, composite soil moisture values in both the ensemble members that forecasted and did not forecast flash drought were above normal, similar to conditions indicated by the ERA5 reanalysis (Fig. 9a). While both composites predict development of drought conditions, the difference lies in the rate of

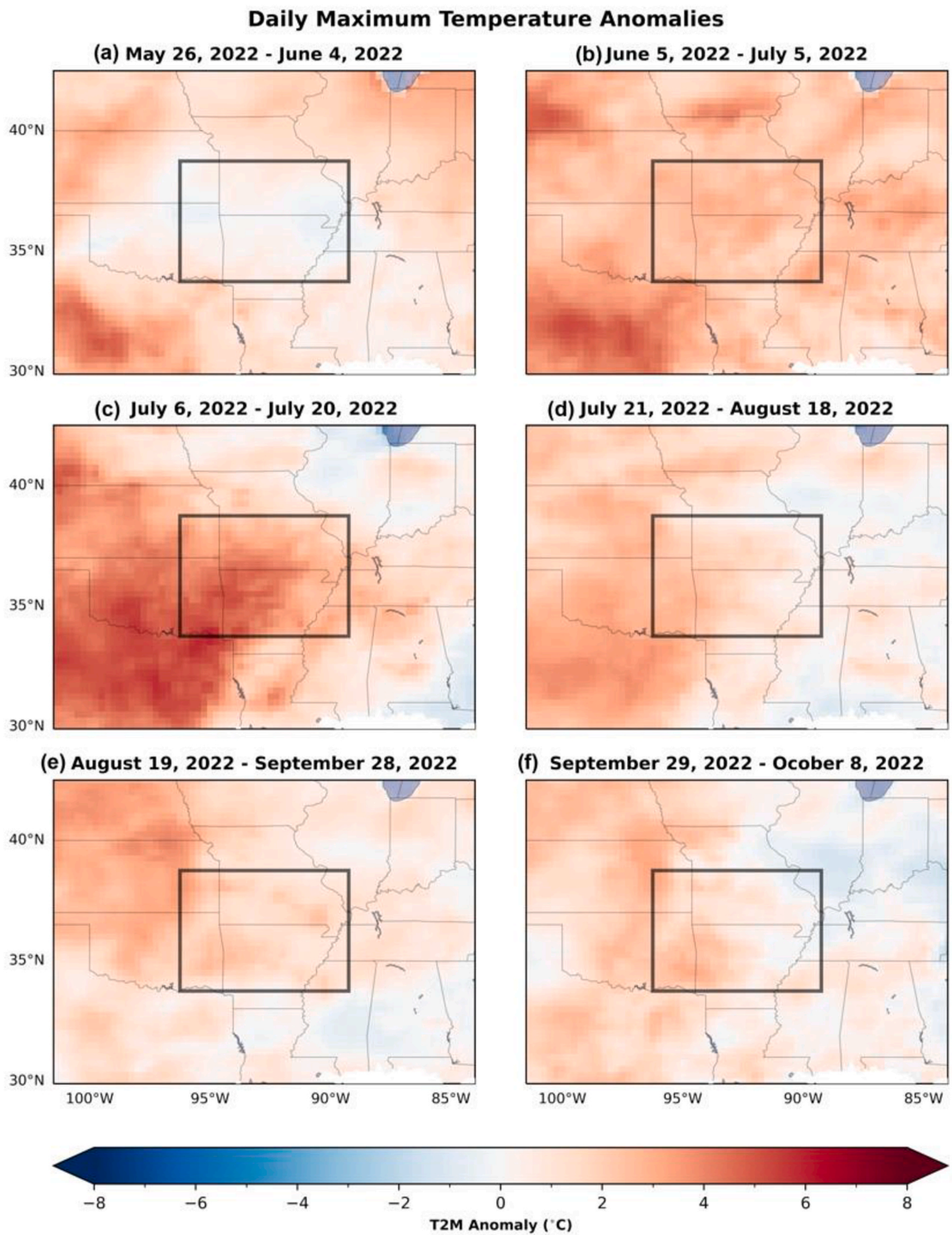


Fig. 6. 2-Meter daily maximum temperature anomalies (°C) during a) the period prior to the flash drought event, b) the first flash drought event, c) the drought persistence period, d) the recovery period, e) the second flash drought event, and f) the period following the second flash drought event.

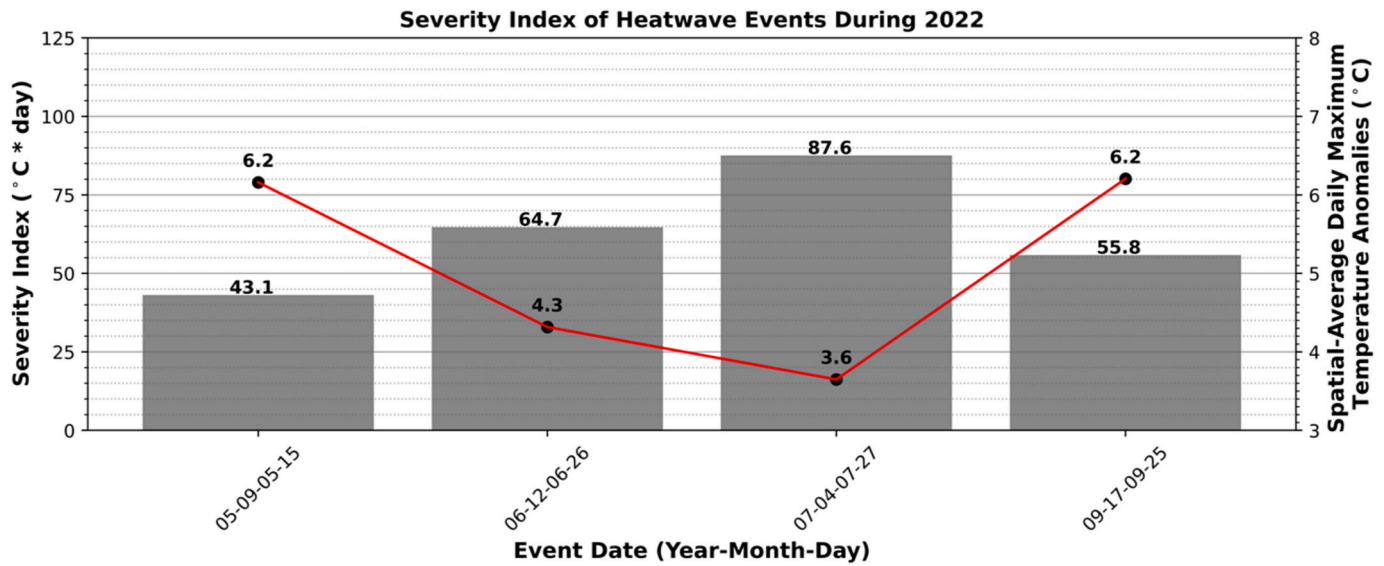


Fig. 7. Heatwave severity index (°C-day; bars) and temperature anomalies (°C; red line) for the four heatwave events during the warm season of 2022. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

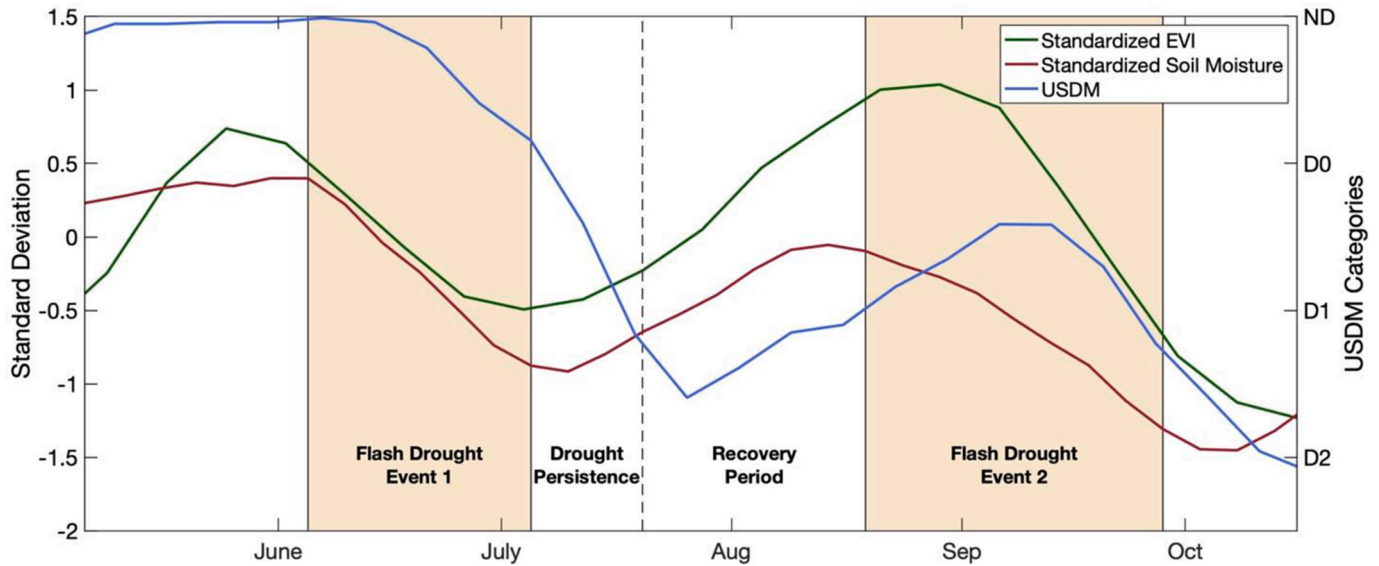


Fig. 8. Domain-averaged standardized EVI from MODIS, standardized soil moisture from ERA5, and USDM categories. The domain for areal-averaged variables is shown in Fig. 1b–e. The tan shaded region indicates median flash drought timing for grid points located in the domain.

drought intensification. The 20% of ensemble members that forecast flash drought closely follow the rapid soil moisture depletion as shown with ERA5 soil moisture (Fig. 9a). The 80% of ensemble members that did not forecast flash drought still predicted drought development, but at a slower pace (Fig. 9a). A similar result is seen for FD2, with a faster rate of soil desiccation in the ensemble members that predicted flash drought versus those that did not (Fig. 9b). Both composites predicted standardized soil moisture values that were greater than those from ERA5 at the onset of FD2 in mid-August (Fig. 9b). However, the ensemble members that didn't forecast flash drought had notably higher soil moisture values by end of August, limiting the potential for flash drought development.

To explore the upper-level atmospheric wave patterns associated with the flash drought events in the S2S models, 500 hPa geopotential heights were averaged during each event (5 June – 5 July FD1, and 19 August – 28 September for FD2; Fig. 10). Composites were produced from ensemble members that did identify flash drought and those that

did not. For FD1, the mid-tropospheric circulation pattern was similar between the composites that did produce a flash drought versus those that did not forecast flash drought, with a large ridge feature centered over the west-central United States, positive height anomalies upstream of the ridge axis, and negative height anomalies downstream of the ridge axis (Fig. 10a and b). However, a notable difference is seen over the study domain, with positive height anomalies over the south-central United States in the ensembles that predicted flash drought, and is further highlighted in the difference between the ensemble composites (Fig. 10a–c). This acted to broaden the ridge across the United States, similar to the pattern seen in the ERA5 analysis in Fig. 3a.

During FD2, both sets of composites depicted positive 500 hPa geopotential height anomalies in the northwest United States with the ridge axis over the west-central United States, similar to the pattern seen during FD1 (Fig. 10d and e). However, the key difference in FD2 was the more amplified wave pattern across the United States predicted by the ensemble members that did produce flash drought versus those that did

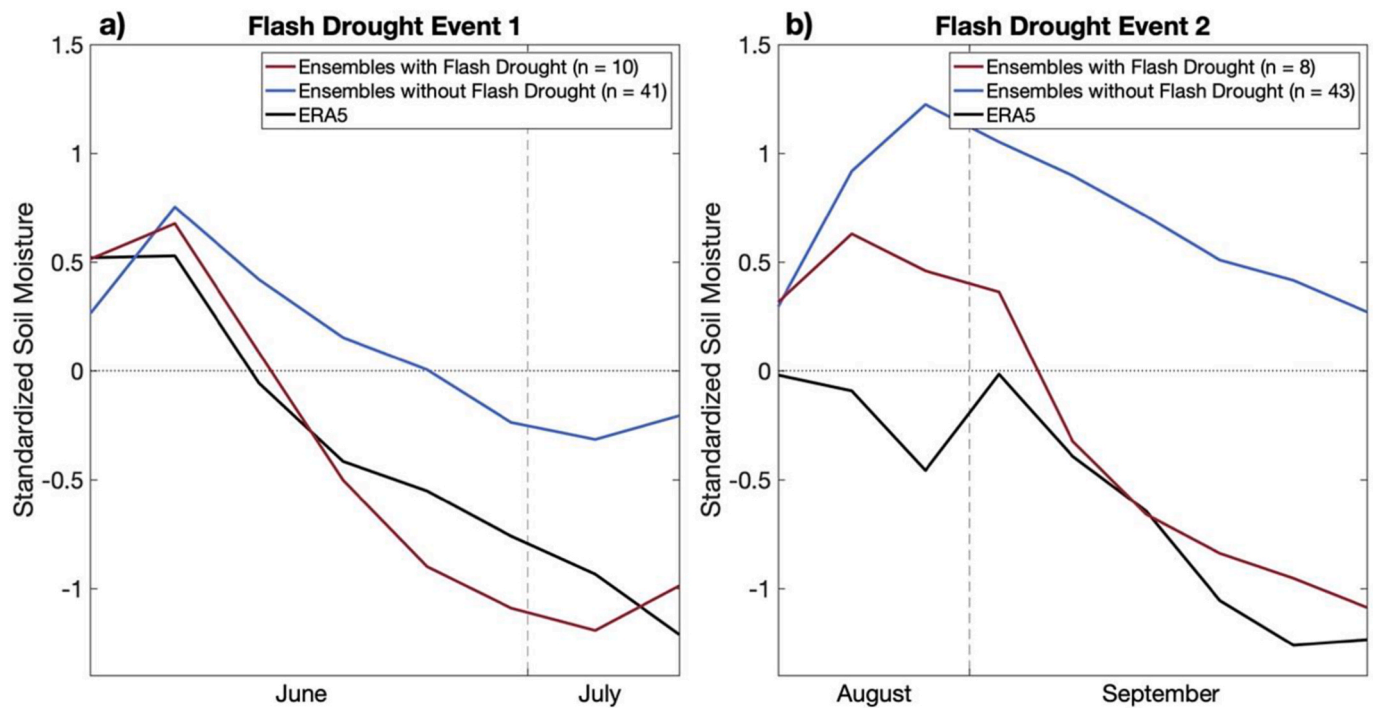


Fig. 9. (a) Composite of standardized soil moisture from ECMWF S2S ensemble members that captured flash drought (red line) and did not capture flash drought (blue line) during FD1. ERA5 standardized soil moisture (i.e., verification) shown in black line. (b) As in (a) but for FD2. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

not (i.e., larger, positive height anomalies over the ridge axis and lower height anomalies over the trough axis; Fig. 10f). Ensemble members that did produce flash drought closely follow the atmospheric pattern seen in the ERA5 analysis (Fig. 3d).

3.3. Impacts

The sequence of two consecutive flash drought events in the south-central United States led to a wide array of impacts across environmental and agricultural sectors. The rapid development of drought conditions was captured by a diverse range of drought indicators, including root zone soil moisture, vegetation health, and the USDM (Fig. 8). Rapid soil moisture declines occurred concurrently with rapid declines in SESR during both flash drought events, however, lagged relationships of SESR and soil moisture declines with EVI and the USDM were also evident (Figs. 1a and 8). Drought conditions via the USDM began to decline approximately two weeks after FD1 began, but the average drought category across the south-central United States rapidly degraded in late June and July, approaching D2 drought conditions by July 26, 2022 across the study domain. A similar response in the USDM was seen in FD2, with the USDM indicating the beginning of worsening drought conditions three weeks after flash drought onset was detected by SESR. Nonetheless, rapid drought development was detected by the USDM in late September and early October, with D3 drought conditions spanning nearly the entire study domain. Lastly, EVI had two different lagged responses to flash drought development with respect to SESR and soil moisture. During FD1, declines in vegetation health were detected by EVI 1–2 weeks prior to the onset of rapid declines in SESR and soil moisture. In contrast, after a period of precipitation allowed vegetation health to recover to conditions slightly above average by late August, rapid declines in EVI lagged the onset of flash drought via SESR by approximately two weeks. Advance lead time in flash drought development using vegetation indices was also noted during the 2012 flash drought in the south-central United States (Christian et al., 2022). In situations where early and above-average green-up occurs,

satellite-based vegetation indices can detect the initial period of land surface desiccation in flash drought onset prior to large declines in soil moisture are rapid increases in evaporative stress (Ault et al., 2013; Christian et al., 2022).

The spatial evolution of the land surface desiccation associated with the two flash drought events can be further evaluated with standardized EVI (Fig. 11). Upon flash drought onset during FD1, anomalously high EVI values were present in most of the study area indicating above-average vegetation growth. Approximately 16 days after onset, EVI anomalies began to decrease; however, most of the study remained above the climatological mean. Significant impacts on vegetative health did not occur until the end of the period of rapid drought intensification. Overall, large negative anomalies existed in EVI by early July, indicating vegetative stress or damage. However, areas of anomalously high values remained within the flash drought domain. This difference may be attributed to land cover type as some land cover types are more resilient to flash drought. In particular, forests with deeper root systems have been shown to respond slower to flash drought impacts than croplands or grasslands with shallow root systems (Liu et al., 2020; Yao et al., 2022). After the period of precipitation from late July to mid-August, much of the domain experienced a recovery in vegetative health, most notably in the eastern portion of the study domain. Similar to the first event, much of the eastern study domain remained above the climatological mean 16 days after flash drought onset during the second event. For both events, vegetative health did not decline to values below normal until approximately 16 days after onset. By the end of FD2, significant decreases in EVI were present for much of the domain with limited areas of resilience to flash drought.

Impacts from the flash drought events were also experienced by agricultural producers. Prior to the first flash drought event, drought conditions were non-existent over the domain (Supplementary Fig. 1a). Once rapid intensification began, impacts to the agricultural community quickly followed. For example, pasture conditions across Arkansas revealed a rapid decline in pastureland conditions immediately following the start of the first flash drought event (Supplementary

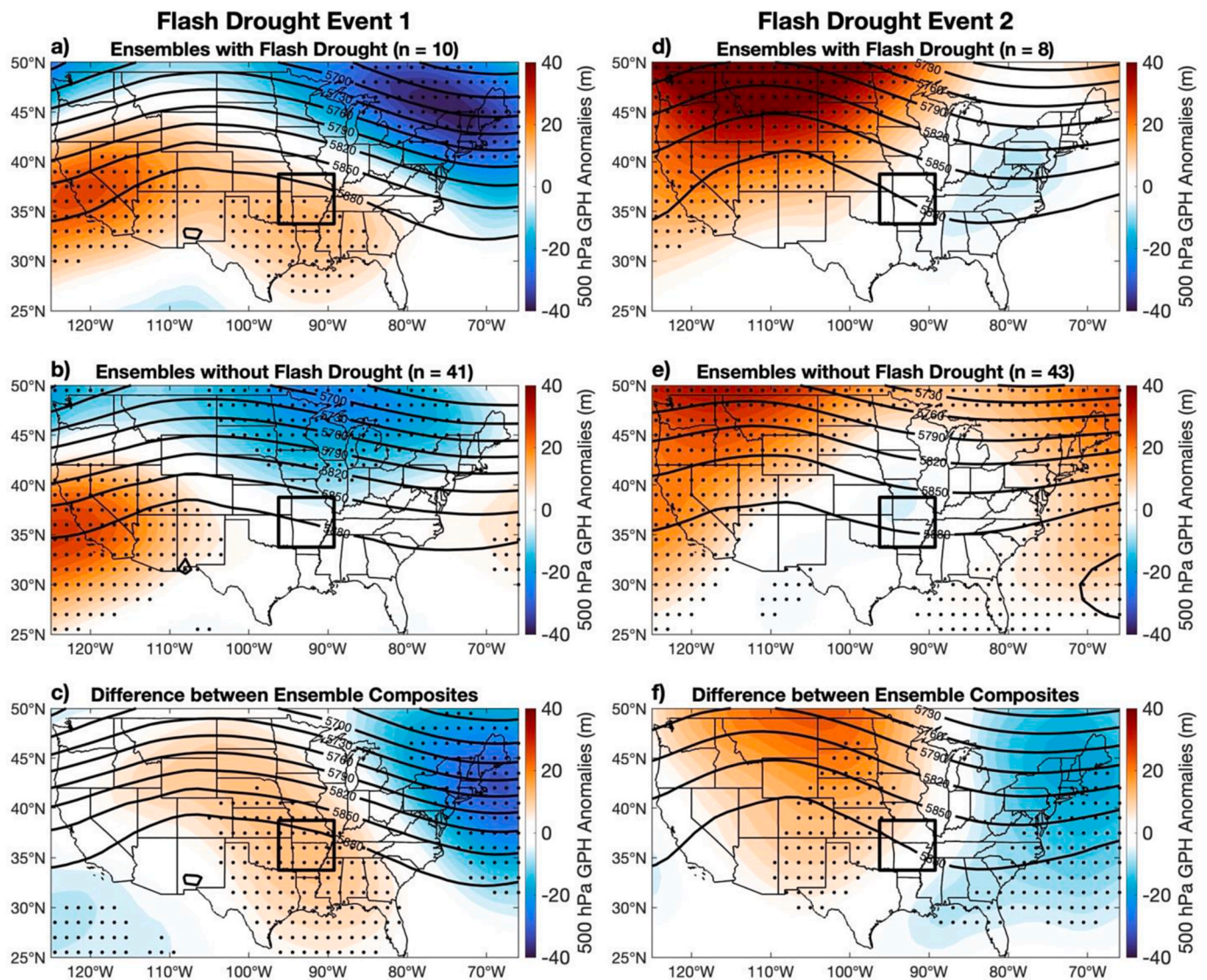


Fig. 10. Composite of 500 hPa geopotential heights (m; black contours) and anomalies (m; shaded contours) from ECMWF S2S ensembles that captured flash drought (a,d) and did not capture flash drought (b,e) for the two flash drought events. Difference in 500 hPa geopotential height anomalies between the composites is also shown for FD1 (c) and FD2 (f). Black stippling denotes statistical significance at the 99% confidence level. Study domain is indicated with the black rectangle.

Fig. 6). Conditions improved during the month of August due to increased precipitation during the relief period; however, conditions deteriorated further during the second flash drought event. As a result of the flash drought events in conjunction with several heatwaves, agricultural producers took action to limit losses. Beginning in July, producers within southern Missouri were forced to sell their cattle due to drought-stricken areas not having sufficient forage for grazing (Turner 2022). Further, throughout the late summer and into the fall as FD2 transpired, livestock producers in Oklahoma were forced to sell large herds of cattle due to limited water availability amidst dire drought conditions, aiding in a 12% reduction of the state's total cattle population (Felder 2022). The occurrence of back-to-back flash drought events extenuated the duration of impacts, resulting in severe consequences to agricultural producers.

The enhanced risk of wildfires is another major impact of the flash droughts. Notably after the rapid intensification phase of FD2, increased fire weather conditions were observed over the study area. The Arkansas Department of Agriculture reported that in October 2022, over 50% of the entire landmass of Arkansas was under a “burn ban”. Moreover, the entire state of Arkansas was placed under an alert as most areas ranged between medium to high risks of having wildfire breakouts (Jared

2022). Of the four critical ingredients for enhanced wildfire risk (i.e., high temperatures, low humidity, dry fuels/vegetation, and strong winds), FD2 led to three of these ingredients, with (1) a significant depletion of soil moisture reducing latent heat flux and low-level atmospheric humidity (Figs. 2 and 8), (2) above-average temperatures following the period of rapid drought intensification (Fig. 1a), and (3) considerable drying in vegetation as indicated by EVI (Figs. 8 and 11). This was evident given the numerous wildfires that occurred during the summer and fall of 2022 (Supplementary Fig. 7).

Finally, the sequence of two consecutive flash drought events also led to hydrologic impacts. In June and July, the Mississippi River saw a decrease in its gauge and stream flow due to its direct river basin being impacted by the flash droughts (Lombardi et al., 2022; Rembert 2023). While water levels in the river were able to recover partly during August, the gauge height decreased again during FD2 to near record-breaking levels in October (Fig. 12; (Lombardi et al., 2022; Rembert 2023; Jared 2023). The low river levels hindered and delayed the transportation of food and supplies by barge along the river. As such, the congested barge traffic disrupted the supply chain along the Mississippi river and caused an increase in the average cost of transportation on the Mississippi River via barge by more than 6-fold during the peak of the

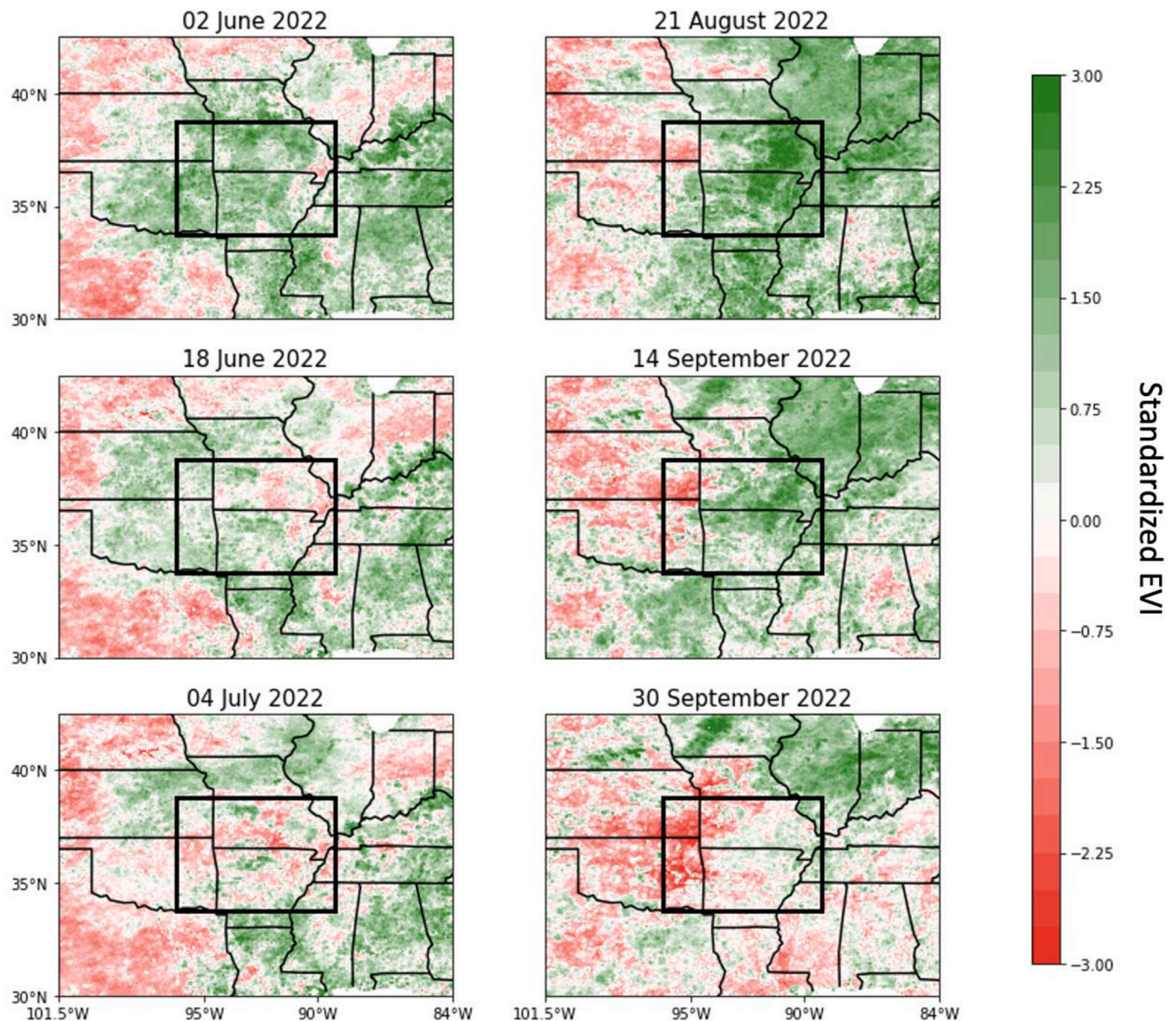


Fig. 11. Standardized EVI anomalies (representing vegetation health) during the start, middle, and end of (left column) FD1 and (right column) FD2.

drought in October, when the Mississippi River was at its lowest gauge height (Lombardi et al., 2022; Oxner and McMinn 2022; Fortin 2022). While conditions improved after the drought, the average cost for barge transportation remained around a 2.5-fold increase in November, compared to pre-drought values, due to increased need to transport food.

4. Conclusions

The flash drought-recovery-flash drought sequence across the south-central United States during the warm season of 2022 was a rare set of events that led to compound and cascading impacts across the region. The key atmospheric pattern featured a persistent upper-level ridge either directly over the study area (FD1) or shifted west and upstream of the region where flash drought occurred (FD2). Both atmospheric patterns drove broad-scale subsidence, reduced mid-level moisture, limited the development of precipitation, and increased the evaporative demand. Furthermore, the heatwave events that occurred throughout the summer and fall were both drivers of and driven by the two flash drought events. The heatwave that occurred during the middle of FD1

assisted in driving rapid drought intensification due to increased evaporative demand, while the heatwave that developed after FD1 was amplified by land surface desiccation following rapid drought intensification and resulted from land-atmosphere feedbacks coupled with synoptic forcing. The last heatwave in the warm season was a “hybrid” event that both assisted in driving rapid drought development toward the end of FD2 and was reinforced by land-atmospheric feedbacks via the notably dry land surface. Between the two flash drought events, the recovery period was characterized with a more active synoptic pattern and associated rainfall.

Some predictive skill for the two flash drought events was seen in the ECMWF S2S model, with 20% of the ensembles predicting flash drought during FD1 and 16% for FD2. While ensembles composites that forecasted and did not forecast flash drought both predicted the development of drought conditions for FD1 and FD2, ensembles that produced rapid drought intensification were associated with positive 500 hPa geopotential height anomalies over the south-central United States (FD1) or an amplified wave pattern (FD2) with the ridge axis centered over the west-central United States. While this study provided an initial assessment in the ability of S2S models to capture flash drought

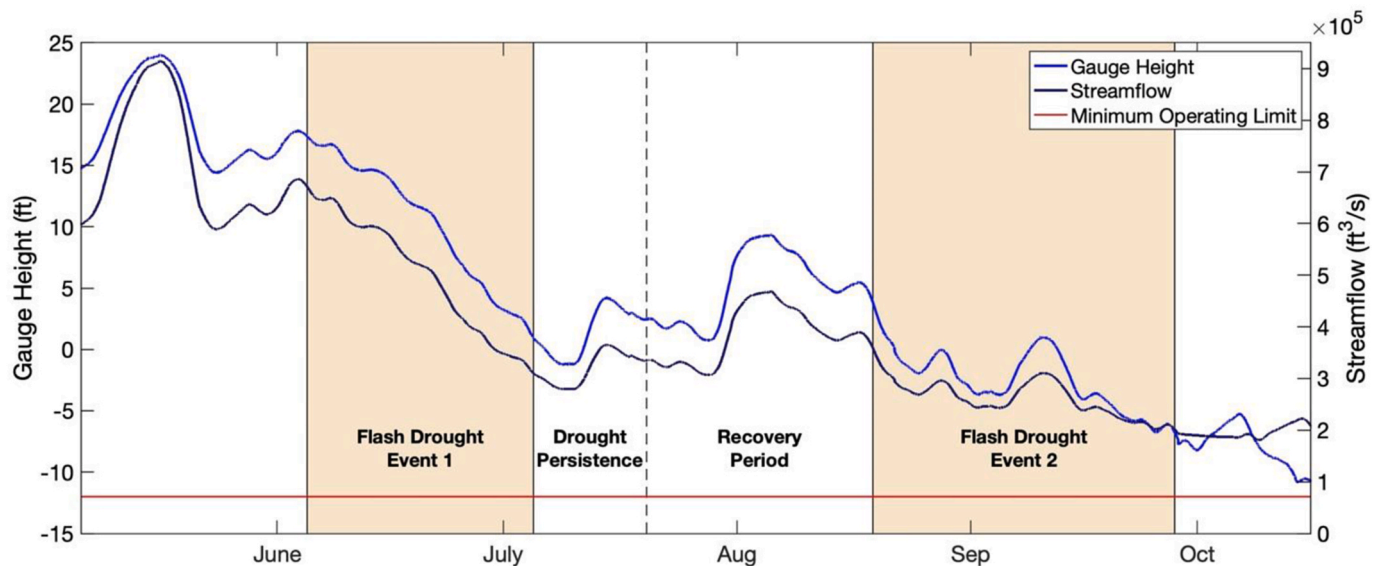


Fig. 12. Gauge height and streamflow for the Mississippi River at Memphis, TN (USGS 0 7032000). The tan shaded region indicates median flash drought timing for grid points located in the domain.

development at event onset, future work should investigate the predictive skill of models to predict flash drought onset as a function of forecast lead time. Additionally, future work should examine if certain indices (e.g., soil moisture, SESR, etc.) have higher predictive skill of flash drought development on S2S timescales.

A vast array of drought indicators (e.g., the USDM, soil moisture, EVI) revealed rapid drought intensification and drought severity from both flash drought events. Overall, the combination of the two flash drought events led to agricultural, environmental, and hydrologic impacts. These impacts included a rapid reduction in pastureland conditions, widespread cattle selloff, vegetative and land surface desiccation, increased risk of wildfire development, and reduced runoff resulting in a large decline in gauge height and stream flow within the Mississippi River east of the study domain. The occurrence of the back-to-back flash drought events and their associated impacts further demonstrates the need for progress in the development of near-time monitoring of flash drought, advancements and improvements in S2S predictability of flash drought, and continued research to increase our understanding of the compound and cascading impacts of flash drought.

Availability Statement

Variables and derived variables used in this study from ERA5 are available at <https://cds.climate.copernicus.eu>, EVI from MODIS is available at <https://search.earthdata.nasa.gov/>, and USDM data is available at <https://droughtmonitor.unl.edu/DmData/GISData.aspx>. ECWMF S2S model data is available at <https://apps.ecmwf.int/datasets/>.

CRediT authorship contribution statement

Jordan I. Christian: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Taylor M. Grace:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Benjamin J. Fellman:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Daniel F. Mesherke:** Writing – review & editing, Writing – original draft, Formal analysis. **Stuart G. Edris:** Writing – review & editing, Writing – original draft, Formal analysis. **Henry O. Olayiwola:** Writing – review & editing, Writing – original draft. **Jeffrey B. Basara:** Writing – review & editing. **Brian A. Fuchs:**

Writing – review & editing. **Jason C. Furtado:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.wace.2024.100730>.

References

- Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements. *FAO Irrigation and Drainage. Paper 56*.
- Anderson, G.B., Bell, M.L., 2011. Heat waves in the United States: mortality risk during heat waves and effect modification by heat wave characteristics in 43 U.S. Communities. *Environ. Health Perspect.* 119, 210–218. <https://doi.org/10.1289/ehp.1002313>.
- Ault, T.R., Henebry, G.M., de Beurs, K.M., Schwartz, M.D., Betancourt, J.L., Moore, D., 2013. The false spring of 2012, earliest in north American record. *Eos, Trans. Am. Geophys. Union* 94, 181–182. <https://doi.org/10.1002/2013eo200001>.
- Bajgain, R., Xiao, X., Wagle, P., Basara, J., Zhou, Y., 2015. Sensitivity analysis of vegetation indices to drought over two tallgrass prairie sites. *ISPRS J. Photogrammetry Remote Sens.* 108, 151–160. <https://doi.org/10.1016/j.isprsjprs.2015.07.004>.
- Basara, J.B., Christian, J.I., Wakefield, R.A., Otkin, J.A., Hunt, E.H., Brown, D.P., 2019. The evolution, propagation, and spread of flash drought in the Central United States during 2012. *Environ. Res. Lett.* 14, 084025. <https://doi.org/10.1088/1748-9326/ab2cc0>.
- Chen, J., Jönsson, Per, Tamura, M., Gu, Z., Matsushita, B., Eklundh, L., 2004. A simple method for reconstructing a high-quality NDVI time-series data set based on the Savitzky–Golay filter. *Remote Sens. Environ.* 91, 332–344. <https://doi.org/10.1016/j.rse.2004.03.014>.

- Chen, L.G., Gottschalk, J., Hartman, A., Miskus, D., Tinker, R., Artusa, A., 2019. Flash drought characteristics based on U.S. Drought monitor. *Atmosphere-basel* 10, 498. <https://doi.org/10.3390/atmos10090498>.
- Christian, J.I., Coauthors, 2023. Global projections of flash drought show increased risk in a warming climate. *Commun. Earth Environ.* 4, 165. <https://doi.org/10.1038/s43247-023-00826-1>.
- Christian, J.I., Coauthors, 2024. Flash drought: a state of the science review. *Wiley Interdiscip. Rev.: Water*. <https://doi.org/10.1002/wat2.1714>.
- Christian, J., Christian, K., Basara, J.B., 2015. Drought and pluvial dipole events within the Great plains of the United States. *J. Appl. Meteorol. Climatol.* 54, 1886–1898. <https://doi.org/10.1175/jamc-d-15-0002.1>.
- Christian, J.I., Basara, J.B., Otkin, J.A., Hunt, E.D., Wakefield, R.A., Flanagan, P.X., Xiao, X., 2019. A methodology for flash drought identification: application of flash drought frequency across the United States A methodology for flash drought identification: application of flash drought frequency across the United States. *J. Hydrometeorol.* 20, 833–846. <https://doi.org/10.1175/jhm-d-18-0198.1>.
- Christian, J.I., Basara, J.B., Hunt, E.D., Otkin, J.A., Xiao, X., 2020. Flash drought development and cascading impacts associated with the 2010 Russian heatwave. *Environ. Res. Lett.* 15, 094078. <https://doi.org/10.1088/1748-9326/ab9faf>.
- Christian, J.I., Basara, J.B., Hunt, E.D., Otkin, J.A., Furtado, J.C., Mishra, V., Xiao, X., Randall, R.M., 2021. Global distribution, trends, and drivers of flash drought occurrence. *Nat. Commun.* 12, 6330. <https://doi.org/10.1038/s41467-021-26692-z>.
- Christian, J.I., Lowman, L.E.L., Xiao, X., Mesheske, D., Zhou, Y., 2022. Flash drought identification from satellite-based land surface water index. *Remote Sens Appl Soc Environ* 26, 100770. <https://doi.org/10.1016/j.rsase.2022.100770>.
- DeAngelis, A.M., Wang, H., Koster, R.D., Schubert, S.D., Chang, Y., Marshak, J., 2020. Prediction skill of the 2012 U.S. Great plains flash drought in subseasonal experiment (SubX) models. *J. Clim.* 33, 6229–6253. <https://doi.org/10.1175/jcli-d-19-0863.1>.
- Domeisen, D.I.V., Coauthors, 2023. Prediction and projection of heatwaves. *Nat. Rev. Earth Environ.* 4, 36–50. <https://doi.org/10.1038/s43017-022-00371-z>.
- Dong, X., Coauthors, 2011. Investigation of the 2006 drought and 2007 flood extremes at the Southern Great Plains through an integrative analysis of observations. *J. Geophys. Res. Atmos.* 116. <https://doi.org/10.1029/2010jd014776>.
- Felder, B., 2022. As drought worsens, Oklahoma ranchers look to the state for relief. *The Oklahoman*, September 25. <https://www.oklahoman.com/story/news/politics/government/2022/09/25/oklahoma-weather-drought-is-a-crisis-for-many-ranchers/69503891007/>.
- Flanagan, P.X., Basara, J.B., Xiao, X., 2017. Long-term analysis of the asynchronicity between temperature and precipitation maxima in the United States Great Plains: great plains temperature and precipitation maxima asynchronicity. *Int. J. Climatol.* 37, 3919–3933. <https://doi.org/10.1002/joc.4966>.
- Ford, T.W., Labosier, C.F., 2017. Meteorological conditions associated with the onset of flash drought in the Eastern United States. *Agric. For. Meteorol.* 247, 414–423. <https://doi.org/10.1016/j.agrformet.2017.08.031>.
- Ford, T.W., McRoberts, D.B., Quiring, S.M., Hall, R.E., 2015. On the utility of in situ soil moisture observations for flash drought early warning in Oklahoma, USA. *Geophys. Res. Lett.* 42, 9790–9798. <https://doi.org/10.1002/2015gl066600>.
- Fortin, J., 2022. Shrunken Mississippi River Snares Barge Traffic and Imperils Drinking Supplies. *New York Times*.
- Fu, K., Wang, K., 2022. Quantifying flash droughts over China from 1980 to 2017. *J. Geophys Res Atmospheres* 127. <https://doi.org/10.1029/2022jd037152>.
- Hattis, D., Ognéva-Himmelberger, Y., Ratik, S., 2012. The spatial variability of heat-related mortality in Massachusetts. *Appl. Geogr.* 33, 45–52. <https://doi.org/10.1016/j.apgeog.2011.07.008>.
- He, M., Kimball, J.S., Yi, Y., Running, S., Guan, K., Jensco, K., Maxwell, B., Maneta, M., 2019. Impacts of the 2017 flash drought in the US Northern plains informed by satellite-based evapotranspiration and solar-induced fluorescence. *Environ. Res. Lett.* 14, 074019. <https://doi.org/10.1088/1748-9326/ab22c3>.
- Hersbach, H., Coauthors, 2020. The ERA5 global reanalysis. *Q. J. Roy. Meteorol. Soc.* 146, 1999–2049. <https://doi.org/10.1002/qj.3803>.
- Hoell, A., Coauthors, 2020. Lessons learned from the 2017 flash drought across the U.S. Northern Great plains and Canadian prairies. *Bull. Am. Meteorol. Soc.* 101, E2171–E2185. <https://doi.org/10.1175/bams-d-19-0272.1>.
- Hoerling, M., Eischeid, J., Kumar, A., Leung, R., Mariotti, A., Mo, K., Schubert, S., Seager, R., 2014. Causes and predictability of the 2012 Great plains drought. *Bull. Am. Meteorol. Soc.* 95, 269–282. <https://doi.org/10.1175/bams-d-13-00055.1>.
- Huete, A., Didan, K., Miura, T., Rodriguez, E.P., Gao, X., Ferreira, L.G., 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sens. Environ.* 83, 195–213. [https://doi.org/10.1016/s0034-4257\(02\)00096-2](https://doi.org/10.1016/s0034-4257(02)00096-2).
- Jared, G., 2022. Arkansas at High Wildfire Risk as Dry Conditions Worsen. October 3.
- Jared, G., 2023. Northeast Arkansas abnormally dry as Mississippi River levels drop. <https://talkbusiness.net/2023/06/northeast-arkansas-abnormally-dry-as-mississippi-river-levels-drop/>.
- Jin, C., Luo, X., Xiao, X., Dong, J., Li, X., Yang, J., Zhao, D., 2019. The 2012 flash drought threatened US midwest agroecosystems. *Chin. Geogr. Sci.* 29, 768–783. <https://doi.org/10.1007/s11769-019-1066-7>.
- Liu, X., He, B., Guo, L., Huang, L., Chen, D., 2020. Similarities and differences in the mechanisms causing the European summer heatwaves in 2003, 2010, and 2018. *Earth's Future* 8. <https://doi.org/10.1029/2019ef001386>.
- Lombardi, R., Antipova, A., Burnette, D.J., 2022. Record low water levels on the Mississippi River in 2022 show how climate change is altering large rivers. *The Conversation*. <https://theconversation.com/record-low-water-levels-on-the-mississippi-river-in-2022-show-how-climate-change-is-altering-large-rivers-193920>.
- Lowman, L.E.L., Christian, J.I., Hunt, E.D., 2023. How land surface characteristics influence the development of flash drought through the drivers of soil moisture and vapor pressure deficit. *J. Hydrometeorol.* 24, 1395–1415. <https://doi.org/10.1175/jhm-d-22-0158.1>.
- Ma, R., Yuan, X., 2023. Subseasonal ensemble prediction of flash droughts over China. *J. Hydrometeorol.* 24, 897–910. <https://doi.org/10.1175/jhm-d-22-0150.1>.
- Mahto, S.S., Mishra, V., 2023. Increasing risk of simultaneous occurrence of flash drought in major global croplands. *Environ. Res. Lett.* 18, 044044. <https://doi.org/10.1088/1748-9326/acc8ed>.
- Mukherjee, S., Mishra, A.K., 2022. Global flash drought analysis: uncertainties from indicators and datasets. *Earth's Future* 10. <https://doi.org/10.1029/2022ef002660>.
- Namias, J., 1983. Some causes of United States drought. *J. Clim. Appl. Meteorol.* 22, 30–39. [https://doi.org/10.1175/1520-0450\(1983\)022<0030:scousd>2.0.co;2](https://doi.org/10.1175/1520-0450(1983)022<0030:scousd>2.0.co;2).
- National_Centers_for_Environmental_Information, 2024. Billion-dollar weather and climate disasters. <https://www.ncei.noaa.gov/access/billions/events>.
- National Drought Mitigation Center, 2023. NDMC blends. <https://ndmcblends.unl.edu/Archive.aspx>. (Accessed 26 June 2023).
- Nguyen, H., Wheeler, M.C., Hendon, H.H., Lim, E.-P., Otkin, J.A., 2021. The 2019 flash droughts in subtropical eastern Australia and their association with large-scale climate drivers. *Weather Clim. Extrem.* 32, 100321. <https://doi.org/10.1016/j.wace.2021.100321>.
- Osman, M., Zaitchik, B.F., Badr, H.S., Christian, J.I., Tadesse, T., Otkin, J.A., Anderson, M.C., 2021. Flash drought onset over the contiguous United States: sensitivity of inventories and trends to quantitative definitions. *Hydrol. Earth Syst. Sci.* 25, 565–581. <https://doi.org/10.5194/hess-25-565-2021>.
- Otkin, J.A., Coauthors, 2021. Development of a flash drought intensity index. *Atmosphere-basel* 12, 741. <https://doi.org/10.3390/atmos12060741>.
- Otkin, J.A., Coauthors, 2022. Getting ahead of flash drought: from early warning to early action. *Bull. Am. Meteorol. Soc.* 103, E2188–E2202. <https://doi.org/10.1175/bams-d-21-0288.1>.
- Otkin, J.A., Anderson, M.C., Hain, C., Mladenova, I.E., Basara, J.B., Svoboda, M., 2013. Examining rapid onset drought development using the thermal infrared-based evaporative stress index. *J. Hydrometeorol.* 14, 1057–1074. <https://doi.org/10.1175/jhm-d-12-0144.1>.
- Otkin, J.A., 2016. Assessing the evolution of soil moisture and vegetation conditions during the 2012 United States flash drought. *Agric. For. Meteorol.* 218, 230–242. <https://doi.org/10.1016/j.agrformet.2015.12.065>.
- Otkin, J.A., Svoboda, M., Hunt, E.D., Ford, T.W., Anderson, M.C., Hain, C., Basara, J.B., 2018. Flash droughts: A review and assessment of the challenges imposed by rapid-onset droughts in the United States. *B. Am. Meteorol. Soc.* 99, 911–919. <https://doi.org/10.1175/bams-d-17-0149.1>.
- Otkin, J.A., Zhong, Y., Hunt, E.D., Basara, J., Svoboda, M., Anderson, M.C., Hain, C., 2019. Assessing the evolution of soil moisture and vegetation conditions during a flash drought–flash recovery sequence over the south-Central United States. *J. Hydrometeorol.* 20, 549–562. <https://doi.org/10.1175/jhm-d-18-0171.1>.
- Oxner, T., McMin, J., 2022. Low Water Levels on the Mississippi River and its Impact on Arkansas Producers. *Arkansas Farm Bureau*.
- Parker, T., Gallant, A., Hobbins, M., Hoffmann, D., 2021. Flash drought in Australia and its relationship to evaporative demand. *Environ. Res. Lett.* 16, 064033. <https://doi.org/10.1088/1748-9326/abfe2c>.
- Pegion, K., Coauthors, 2019. The subseasonal experiment (SubX): a multimodel subseasonal prediction experiment. *Bull. Am. Meteorol. Soc.* 100, 2043–2060. <https://doi.org/10.1175/bams-d-18-0270.1>.
- Pendergrass, A.G., Coauthors, 2020. Flash droughts present a new challenge for subseasonal-to-seasonal prediction. *Nat. Clim. Change* 10, 191–199. <https://doi.org/10.1038/s41558-020-0709-0>.
- Rembert, E., 2023. Flash Droughts Are Becoming a Bigger Threat to Crops, Water, Supply, Shipping, Research Says. *KCUR, NPR in Kansas City*.
- Ruiz-Barradas, A., Nigam, S., 2005. Warm season rainfall variability over the U.S. Great plains in observations, NCEP and ERA-40 reanalyses, and NCAR and NASA atmospheric model simulations. *J. Clim.* 18, 1808–1830. <https://doi.org/10.1175/jcli3343.1>.
- Schubert, S.D., Chang, Y., DeAngelis, A.M., Wang, H., Koster, R.D., 2021. On the development and demise of the fall 2019 southeast U.S. Flash drought: links to an extreme positive IOD. *J. Clim.* 34, 1701–1723. <https://doi.org/10.1175/jcli-d-20-0428.1>.
- Smith, T.T., Zaitchik, B.F., Gohlke, J.M., 2013. Heat waves in the United States: definitions, patterns and trends. *Clim. Change* 118, 811–825. <https://doi.org/10.1007/s10584-012-0659-2>.
- Steadman, R.G., 1984. A universal scale of apparent temperature. *J. Clim. Appl. Meteorol.* 23, 1674–1687. [https://doi.org/10.1175/1520-0450\(1984\)023<1674:ausoat>2.0.co;2](https://doi.org/10.1175/1520-0450(1984)023<1674:ausoat>2.0.co;2).
- Svoboda, M., Coauthors, 2002. The drought monitor. *Bull. Am. Meteorol. Soc.* 83, 1181–1190. <https://doi.org/10.1175/1520-0477-83.8.1181>.
- Ting, M., Wang, H., 1997. Summertime U.S. Precipitation variability and its relation to Pacific sea surface temperature. *J. Clim.* 10, 1853–1873. [https://doi.org/10.1175/1520-0442\(1997\)010<1853:suspsva>2.0.co;2](https://doi.org/10.1175/1520-0442(1997)010<1853:suspsva>2.0.co;2).
- Trenberth, K.E., Arkin, P.A., 1988. Origins of the 1988 north American drought. *Science* 242, 1640–1645. <https://doi.org/10.1126/science.242.4886.1640>.
- Trenberth, K.E., Branstator, G.W., 1992. Issues in establishing causes of the 1988 drought over north America. *J. Clim.* 5, 159–172. [https://doi.org/10.1175/1520-0442\(1992\)005<0159:ieecot>2.0.co;2](https://doi.org/10.1175/1520-0442(1992)005<0159:ieecot>2.0.co;2).
- Turner, K., 2022. Missouri's Drought Forces Cattlemen to Make Tough Decisions, Parson "Ready to Act if Situation worsens.". *The Missouri Times*. July 20.

- Vitart, F., Coauthors, 2017. The subseasonal to seasonal (S2S) prediction Project Database. *Bull. Am. Meteorol. Soc.* 98, 163–173. <https://doi.org/10.1175/bams-d-16-0017.1>.
- Wagle, P., Coauthors, 2014. Sensitivity of vegetation indices and gross primary production of tallgrass prairie to severe drought. *Remote Sens. Environ.* 152, 1–14. <https://doi.org/10.1016/j.rse.2014.05.010>.
- Wang, M., Menzel, L., Jiang, S., Ren, L., Xu, C.-Y., Cui, H., 2023. Evaluation of flash drought under the impact of heat wave events in southwestern Germany. *Sci. Total Environ.* 904, 166815. <https://doi.org/10.1016/j.scitotenv.2023.166815>.
- Wolf, S., Coauthors, 2016. Warm spring reduced carbon cycle impact of the 2012 US summer drought. *Proc. Natl. Acad. Sci. USA* 113, 5880–5885. <https://doi.org/10.1073/pnas.1519620113>.
- Yao, T., Liu, S., Hu, S., Mo, X., 2022. Response of vegetation ecosystems to flash drought with solar-induced chlorophyll fluorescence over the Hai River Basin, China during 2001–2019. *J. Environ. Manag.* 313, 114947. <https://doi.org/10.1016/j.jenvman.2022.114947>.
- Zhou, Y., Coauthors, 2017. Quantifying agricultural drought in tallgrass prairie region in the U.S. Southern Great Plains through analysis of a water-related vegetation index from MODIS images. *Agric. For. Meteorol* 246, 111–122. <https://doi.org/10.1016/j.agrformet.2017.06.007>.