The Role of Vegetation in Flash Drought Occurrence: A Sensitivity Study Using Community Earth System Model, Version 2

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ABSTRACT: Flash droughts are noted by their unusually rapid rate of onset or intensification, which makes it difficult to anticipate and prepare for them, thus resulting in severe impacts. Although the development of flash drought can be associated with certain atmospheric conditions, vegetation also plays a role in propagating flash drought. This study examines the climatology of warm season (March–September) flash drought occurrence in the United States between 1979 and 2014, and quantifies the possible impacts of vegetation on flash drought based on a set of sensitivity experiments using the Community Earth System Model, version 2 (CESM2). With atmospheric nudging, CESM2 well captures historical flash drought. Compared with NASA’s Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2), and National Climate Assessment–Land Data Assimilation System (NCA-LDAS), CESM2 shows agreement on the high flash drought frequency in the Great Plains and southeastern United States, but overestimates flash drought occurrence in the Midwest. The vegetation sensitivity experiments suggest that vegetation greening can significantly increase the flash drought frequency in the Great Plains and the western United States during the warm seasons through enhanced evapotranspiration. However, flash drought occurrence is not significantly affected by vegetation phenology in the eastern United States and Midwest due to weak land–atmosphere coupling. In response to vegetation greening, the extent of flash drought also increases, but the duration of flash drought is not sensitive to greening. This study highlights the importance of vegetation in flash drought development, and provides insights for improving flash drought monitoring and early warning.

KEYWORDS: Drought; Atmosphere-land interaction; Climate models

1. Introduction

Recurring drought events across various parts of the United States over the past decade have imposed significant environmental and economic damage. For example, the 2011 drought over the south-central United States caused an estimated $7.62 billion in agricultural losses and $755 million in commercial timber loss in Texas alone (Hoerling et al. 2013). The existing drought classifications—meteorological, agricultural, hydrological, ecological, and socioeconomic—are largely determined by environmental or socioeconomic elements impacted by drought (Wilhite and Glantz 1985; Croasby et al. 2017). More recently, scientists have distinguished a subset of drought events, known as flash droughts, that are characterized by both moisture limitation (i.e., the drought) and its rapid intensification (i.e., the flash) (Mo and Lettenmaier 2015; Ford and Labosier 2017; Otkin et al. 2018). Svoboda et al. (2002) first coined the term “flash drought” to draw attention to droughts that develop more rapidly than normal because rapid drought intensification can magnify economic and environmental impacts. For example, large areas of the central United States experienced a 3–5 U.S. Drought Monitor (USDM) category increase in drought severity in a 2-month period during 2012. This is a remarkable rate of intensification. Regions that were experiencing near-normal conditions at the beginning of June that year had fallen into extreme or exceptional drought conditions (equivalent to a 1-in-20-yr or 1-in-50-yr drought event) only 2 months later (Basara et al. 2019). Typical droughts take several months or potentially years to reach its full intensity (Otkin et al. 2018). Otkin et al. (2015) partly attribute the economic losses from the 2012 drought to its unusually rapid intensification.

Recent studies have found that certain meteorological conditions are associated with rapid drought intensification. For example, when precipitation deficits occur alongside other extreme atmospheric anomalies that enhance evaporative demand, the combination of low atmospheric water supply and abundant atmospheric and vegetative water demand quickly depletes soil moisture (Otkin et al. 2013; Anderson et al. 2013; Christian et al. 2019). Otkin et al. (2013) in particular examined the evolution of four flash drought events and found that rapid increases in vegetation moisture stress were associated with elevated air temperature, lower cloud fraction, larger vapor pressure deficit, and higher wind speed—all of which increase evaporative demand. These results were corroborated by Ford and Labosier (2017), who examined flash drought climatology over the 1979–2010 period in the eastern and central United States. Given adequate plant-available soil moisture, rapid increases in evapotranspiration will deplete soil moisture with little to no impact on vegetation health. However, the persistence of these meteorological conditions for days to weeks

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can force a transition from energy-limited to water-limited evapotranspiration as soil moisture approaches the wilting point and vegetation moisture stress sets in (Hunt et al. 2014; Otkin et al. 2019). This can ultimately—and rather abruptly—manifest in flash drought (Hunt et al. 2009; Mozny et al. 2012; Ford et al. 2015). Within this framework of soil–vegetation–atmosphere interactions, the role of vegetation in flash drought is largely passive or reactive to soil moisture depletion. However, recent studies have provided evidence of an active role of vegetation in amplitifying soil moisture decline leading to flash drought via increased transpiration (Otkin et al. 2018; Gerken et al. 2018; Basara et al. 2019). For example, Sun et al. (2015) found that warmer temperatures and adequate precipitation boosted vegetation growth in the spring of 2012. This was followed by an acute dry spell and large, short-term precipitation deficits in the early summer, which, when combined with high temperatures, rapidly depleted soil moisture and led to drought onset in the central Great Plains. The dense springtime vegetation coverage makes the conditions more favorable for evapotranspiration (Mo and Lettenmaier 2015), thus accelerating soil moisture reduction at the early stage of the drought events. Although the importance of vegetation has been recognized in those studies, current understanding of the active role of vegetation in flash drought is severely lacking, especially during the warm season when there is dense vegetation and high water demand. Better knowledge of the impact of vegetation on flash drought occurrence and intensity would help improve flash drought monitoring and early warning systems, which can leverage vegetation information to increase predictive skill.

In this study, we examine the role of vegetation in flash drought occurrence, duration, and extent from a climatological perspective, based on a set of sensitivity experiments in the Community Earth System Model, version 2 (CESM2; Danabasoglu et al. 2020). In particular, this research is motivated by two primary questions: 1) can CESM2 capture flash drought events, and 2) how do flash drought frequency, duration, and extent respond to changes in warm-season leaf area index (LAI) conditions?

2. Methodology

a. CESM experiments

This study uses CESM2 to investigate the impacts of vegetation LAI on flash drought. CESM2 is a state-of-the-art Earth system model, which represents different components of the climate system, such as atmosphere, ocean, land, sea ice, and land ice. As the primary focus of this study is flash drought and land-atmosphere feedback, all the simulations are conducted with the FHIST component set. The FHIST component set allows the active, coupled Community Atmosphere Model (CAM6; Bogenschutz et al. 2018) and Community Land Model (CLM5; Lawrence et al. 2019) but using prescribed transient monthly sea surface temperatures (SSTs) and sea ice concentrations (SICs). The transient SSTs and SICs are derived from the observations for the period 1979–2014 provided by Hurrell et al. (2008). In the vertical dimension, there are 32 atmospheric levels with a top at 2.26 hPa for the atmosphere and 20 soil levels with active hydrology down to 8.5 m for the land (Lawrence et al. 2019). The subgrid hierarchy of CLM5 allows multiple land units (such as natural vegetation, crop, and urban) within a single grid cell, and there can be multiple plant functional types (PFTs) or crop functional types (CFTs) within the land units. To disentangle the complex interactions between climate and vegetation, and to control the variations of vegetation conditions, biogeochemistry in CLM5 is turned off, and the LAI for each PFT is derived from the average monthly Moderate Resolution Imaging Spectroradiometer (MODIS) LAI for the period 2001–03 at 0.05° resolution (Lawrence and Chase 2007).

Table 1 shows information about the sensitivity experiments in this study. The first experiment is a Historical simulation with fully coupled atmosphere and land components in accordance with the Atmospheric Model Intercomparison Project (AMIP) protocol. Considering the model uncertainties, the second experiment is a Control simulation with atmospheric nudging to effectively drive the model states toward observations (Wehri et al. 2019). Following the approach in reference (Wehri et al. 2019, 2018), we relax the horizontal winds toward the 6-hourly European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis (ERA-Interim). The height-dependent nudging is applied to the zonal and meridional winds mostly above the 700-hPa levels so that the large-scale circulation in the upper atmosphere is forced toward ERA-Interim reanalysis values, whereas the nudging strength is zero at the surface so that the boundary layer can evolve freely and still allow for land–atmosphere interactions (Wehri et al. 2018).

On the basis of the Control simulation, we perform two sensitivity experiments with increased LAI of grass and crop PFTs (shown in Fig. S1 in the online supplemental material): the first sensitivity experiment has doubled LAI during spring (March–May), which represents a similar vegetation condition as the 2012 central U.S. drought. The second experiment represents a more extreme condition, in which LAI is doubled throughout the warm season, from March to August. As shown in Sun et al. (2015), over the central Great Plains in spring 2012, solar-induced chlorophyll fluorescence (SIF), which is a good indicator of plant photosynthesis, was almost twice the climatological value. Although the magnitude and timing of the LAI increase are subjective, the goal of our experiments is to investigate the sensitivity of flash drought to the changes in vegetation. The changes in LAI in these two experiments are shown in Fig. 1. We only increase the LAI of grass and crop PFTs for two reasons: 1) previous studies suggest a significant “hot spot” of flash drought occurrence across the Great Plains and Midwest (Mo and Lettenmaier 2016; Koster et al. 2019; Chen et al. 2019; Christian et al. 2019), where grassland and cropland are the dominant land cover types, and 2) these two PFTs exhibit considerable sensitivity to interannual variations in growing-season climate (Wu et al. 2017; Quin and Swann 2017), implying that high LAI variations (e.g., 2 times the climatological
values) for grass and crop PFTs are more plausible than for forest PFTs.

All the experiments are performed at a 0.9° latitude \times 1.25° longitude resolution for the period of 1979–2014 with daily output of top 10-cm soil moisture and other climate variables (such as precipitation and evapotranspiration). It should be noted that our drought evaluation is based on the top 10-cm soil moisture, which is different from the soil moisture variables used in previous studies, e.g., top 40-cm soil moisture in Ford and Labosier (2017), and root-zone (top 1 m) soil moisture in Koster et al. (2019) and Yuan et al. (2019).

Although the surface soil moisture evolves more quickly than the deep-layer soil moisture, our analysis based on the top 10-cm soil moisture can capture the historical flash drought events (see in section 3a). If using the root-zone soil moisture, flash drought frequency shows a consistent pattern with the flash drought derived from the surface soil moisture (Fig. S2). Therefore, the choice of soil moisture variable does not influence the credibility of the identified flash drought in this study. Furthermore, as the surface soil moisture is a recommended variable in the Coupled Model Intercomparison Project phase 6 (CMIP6), our evaluation provides insights into future flash drought assessment using the CMIP6 projections.

b. Flash drought identification

One of the goals of this study is to examine if historical flash drought events can be captured with CESM2. We first convert daily top 10-cm volumetric soil water content to percentile values, following the method in Koster et al. (2019). Using the daily soil moisture output from the Control experiment, for a given grid cell on a given day \( k \), a cumulative distribution function (CDF) of soil moisture was constructed from 180 values: 5 days \((k-6, k-3, k, k+3, \text{ and } k+6)\) from each of the 36 years during the period 1979–2014. Then soil moisture is transformed into a percentile value based on the empirical CDFs. To ensure consistent criteria are employed for drought detection, the same CDFs derived from the Control simulation are used to calculate the soil moisture percentile in the Spring_LAI×2 and Warm_LAI×2 experiments.

Based on the percentile values of daily soil moisture, we calculate the pentad (5-day) average soil moisture. The pentad

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<th>Name</th>
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<td>Historical</td>
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<td>Control</td>
<td>CAM6 with nudging</td>
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<td>Spring_LAI×2</td>
<td>CAM6 with nudging</td>
<td>CLM5 with LAI multiplied by 2.0 in spring (March–May)</td>
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<td>Warm_LAI×2</td>
<td>CAM6 with nudging</td>
<td>CLM5 with LAI multiplied by 2.0 in warm seasons (March–August)</td>
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TABLE 1. Information about the experiments in CESM2. In the atmospheric nudging, the zonal and meridional winds in the upper atmosphere (mostly above 700 hPa) are forced to follow the 6-hourly ERA-Interim, whereas the nudging strength is zero at the surface.
average is used to smooth out short-term fluctuations in soil moisture induced by small rainfall events. The detection of flash drought is based on the following three criteria:

1) A flash drought event starts when the top 10-cm pentad-average soil moisture percentile in a given grid cell drops from at or above the 40th percentile to at or below the 20th percentile in no more than four pentads. The same criterion has been used in Ford and Labosier (2017) to identify rapid soil moisture desiccation. Although the thresholds are subjective, they are determined based on significant experience working with soil moisture data (e.g., Ford and Quiring 2014; Quiring et al. 2016) and have been applied in previous flash drought studies (Koster et al. 2019).

2) To be considered a flash drought, after the decrease to at or below the 20th percentile in criterion 1, the following pentad-average soil moisture has to be at or below the 30th percentile for at least three consecutive pentads. This eliminates events where the soil moisture drops rapidly but then increases only 1 or 2 pentads later if there is a precipitation event. This restriction ensures all events are of sufficient duration to be considered drought and not short-term dry spells.

3) A flash drought event ends when the pentad-average soil moisture is at or above the 30th percentile for two consecutive pentads. This ensures prolonged dry conditions separated by one wetter pentad is not considered two separate droughts.

We test the sensitivity of identified events to the criteria above (not shown). The adjustment of thresholds and additional restrictions do not substantially change the spatial pattern of flash drought occurrence, but only reduce the number of events identified, which is relatively sensitive to the requirement to define “flash” (in criterion 1), and the restriction of drought duration (criterion 2). Additionally, to understand the relationship between regular drought and flash drought, we also apply the criteria 2 and 3 above but without considering the “rapid soil moisture desiccation” in criterion 1 to detect “all-type” drought events. In an all-type drought event, soil moisture drops at or below the 20th percentile without the “within-four-pentad” restriction, and stays at or below the 30th percentile for at least three consecutive pentads.

c. Reanalysis for model evaluation

To evaluate the performance of CESM2, one land and one atmospheric reanalysis datasets are used to compare with the simulated soil moisture and detected flash drought in CESM2. Given the fact that ground-based in situ soil moisture observations are not spatially extensive and high-quality satellite-based soil moisture retrievals [such as Soil Moisture and Ocean Salinity (SMOS) and Soil Moisture Active Passive (SMAP)] do not have a sufficiently long data record, we use daily surface soil moisture derived from the reanalysis system and land data assimilation system. The Modern-Era Retrospective analysis for Research and Applications, version 2 (MERRA-2), from the Global Modeling and Assimilation Office (GMAO) at NASA is a state-of-the-art atmospheric reanalysis that assimilates a vast number of in situ and remote sensing observations (Gelaro et al. 2017; GMAO 2015). The Catchment land surface model is used in the MERRA-2 reanalysis system, which provides soil moisture estimates at a 0.5° latitude × 0.625° longitude resolution. MERRA-2 has been used in previous flash drought analysis (Koster et al. 2019), which provides confidence in using it as the reference data in our evaluation. Because soil moisture estimates can highly depend on the land surface models (Schaake 2004; Xia et al. 2015), we also use soil moisture produced by the National Climate Assessment–Land Data Assimilation System (NCA-LDAS) to avoid the bias from the choice of land surface models (Jasinski et al. 2018, 2019). NCA-LDAS is an integrated terrestrial water analysis system that assimilates multiple remote sensing measurements of the terrestrial water cycle (Kumar et al. 2019). The Noah land surface model implemented within the NASA Land Information System (LIS) is used in the NCA-LDAS simulations, which provide soil moisture estimates at a 0.125° latitude × 0.125° longitude resolution. Moreover, because North American Regional Reanalysis (NARR; Mesinger et al. 2006) was also used in previous flash drought analysis (Christian et al. 2019), soil moisture from NARR is also included in our analysis.

Additionally, we use the gridded precipitation observations from the NOAA Climate Prediction Center (CPC) Unified Gauge-Based Analysis to evaluate the simulated precipitation in CESM2. The CPC dataset is a gauge-based analysis of daily precipitation collected from over 30 000 stations (Chen et al. 2008). It provides the global daily precipitation analysis at a 0.5° latitude × 0.5° longitude resolution from 1979 to the present. It should be noted that the CPC Unified Gauge-Based Analysis and Merged Analysis of Precipitation are also used to bias correct precipitation in MERRA-2 before it feeds the Catchment land surface model.

3. Results

a. Historical flash drought events

Our first goal is to evaluate if CESM2 can capture the historical climatology of flash drought events. Figure 2 shows the standardized anomalies of monthly soil moisture during the 2012 Midwest flash drought event from May to July based on NCA-LDAS and the CESM2 Historical and Control simulations. According to the U.S. Drought Monitor, the drought intensity increased by four or even five drought categories from late May to mid-July (Basara et al. 2019). NCA-LDAS shows the drought intensification in the central United States within fewer than two months (Figs. 2a–c). Compared to results from NCA-LDAS, soil moisture evolution is well captured in the Control run of CESM2 (Figs. 2g–i), with the pattern correlations of 0.59, 0.81, and 0.62 in May, June, and July, respectively (after regridding the NCA-LDAS results to the CESM2 resolution). However, the Historical experiment without atmospheric nudging shows very different soil moisture anomaly patterns (Figs. 2d–f), with the pattern correlations of 0.28, 0.37, and 0.37 in May, June, and July, respectively. Because SSTs are prescribed in the Historical run, the disagreement implies that the oceanic forcing does not play a major role in soil moisture conditions of the central United States during the 2012 drought.
event, and CESM2 cannot accurately represent the atmospheric circulations over the plains. The minor role of oceanic forcing in the 2012 central U.S. drought has been documented in other studies (Hoerling et al. 2014; DeAngelis et al. 2020). On the other hand, the agreement of the Control run with the NCA-LDAS suggests that atmospheric circulation likely plays a major role in the 2012 flash drought, similar to the findings of Hoerling et al. (2014).

Similar results can be found in another flash drought in the southern United States in 2000 (Fig. S3). Both the NCA-LDAS and CESM2 Control run show that the drought started from the Florida panhandle, Georgia, and Alabama in July, and rapidly intensified in Texas, Louisiana, and Arkansas through August and September. This agrees with the flash drought description based on the U.S. Drought Monitor (Chen et al. 2019), while the CESM2 Historical run does not capture the 2000 drought event. Furthermore, we examine the region with flash drought occurrence based on our detection approach (Fig. S4). The CESM2 Control simulation can represent the spatial pattern of the widespread flash drought over the central United States in 2012, and over the southern United States in 2000. Meanwhile, during the relative wet years (such as 1989 and 2010), the Control simulation also agrees with the reanalysis, showing few grids with flash drought occurrence.

b. Climatology of flash drought occurrence

Figure 3 shows flash drought occurrence based on MERRA-2, NCA-LDAS, and the two CESM2 simulations. Both MERRA-2 and NCA-LDAS suggest frequent flash drought events in the central, western, and southeastern United States. The major disagreement between the two datasets appears in Canada. NCA-LDAS shows more frequent flash drought events in western and eastern Canada, which are not present in MERRA-2. This can be associated with the reported issues of the NCA-LDAS forcing, which blends disparate precipitation sources in the United States and Canada (Blankenship et al. 2018). As the major focus of this study is the flash drought in the United States, the discrepancy does not affect the credibility of our assessment. It should be noted that MERRA-2, NCA-LDAS, and CESM2 are at different spatial resolutions. Regridding the datasets into a common spatial resolution (e.g., 0.9° latitude × 1.25° longitude) does not affect the identified flash drought (Figs. S5 and S6), implying that the spatial resolution of gridded soil moisture products may have limited impacts on the flash drought detection. On the other hand, the evident difference between MERRA-2 and NCA-LDAS suggests that land surface models and input observations used in those assimilation systems may play a more important role in simulated soil moisture dynamics. According to a recent study (Li et al. 2020), which evaluated soil moisture from different reanalysis datasets at spatial resolutions ranging from 0.28° to 0.7°, soil moisture at a higher spatial resolution does not outperform the other products in representing soil moisture variability.

The CESM2 Control simulation exhibits agreement with the observations in flash drought occurrence over the central and
southeastern United States. However, it also shows frequent flash drought events in the Midwest, which is absent in the reanalysis and NCA-LDAS. The pattern correlation between CESM2 Control and MERRA-2 (NCA-LDAS) is 0.82 (0.85). There is a generally consistent spatial pattern in flash drought occurrence between the Historical and Control simulations, but much more frequent drought events are found in the Historical simulation. The overestimated flash drought frequency over the Midwest can be associated with the dry biases and higher precipitation variability in CESM2.

Figure S7 shows the difference between the simulated precipitation and observations from the NOAA CPC Unified Gauge-Based Analysis during the warm season. Both the Control and Historical simulations underestimate precipitation in the Midwest, the Great Plains, and northern Mexico, and there are greater biases in the Historical (no nudging) simulation. Previous studies (e.g., Gettelman et al. 2018; Danabasoglu et al. 2020) have also documented the dry biases in similar regions, which are probably related to the absence of propagating mesoscale convective system (Liu et al. 2017; Gettelman et al. 2018; Danabasoglu et al. 2020) and model biases in representing the North American monsoon (Meehl et al. 2020). However, the dry bias alone cannot directly impact flash drought frequency because the flash drought is derived from the percentile soil moisture. Figure S8 shows the difference in coefficient of variation (CV) to quantify the variability of daily precipitation. The region with dry biases shows similar or even higher CV compared to the observations. As drier soil can be more sensitive to precipitation variability, precipitation with a similar or higher CV will lead to higher variability of soil moisture, which could potentially cause more flash drought events. Therefore, the overestimated flash drought can be associated with the combined effects of dry biases and higher precipitation variability in CESM2.

c. Impacts of increased LAI on land surface and atmosphere

Increased vegetation productivity and water uptake will both decrease soil moisture and increase latent heat flux to the atmospheric boundary layer. This will occur until soil moisture is limited to the point that vegetation water use is impacted, which will rapidly decrease latent heat flux. It is through the modification of soil moisture uptake and latent heat flux through which vegetation could induce or augment flash drought. Figure 4 shows the changes in latent heat flux and soil moisture prompted by the doubled LAI. According to Fig. 1, the eastern United States has the largest increase in LAI in spring and summer. However, the greatest response in latent heat flux is mainly found in the Great Plains, Midwest, and the western United States. In the Spring_LAI×2 experiment, the enhanced latent heat flux (LE) depletes soil moisture in spring, and the low soil moisture level, in turn, inhibits LE in summer.

FIG. 3. Occurrence of warm season (March–September) flash drought (number of events per warm season) derived from (a) MERRA-2, (b) NCA-LDAS, and the (c) Historical and (d) Control CESM2 simulations. To keep a consistent temporal coverage among the datasets, results are shown for the period 1980–2014. To facilitate comparison, the MERRA-2 and NCA-LDAS results are calculated using regridded soil moisture at the same spatial resolution as the CESM2 simulations.
If the LAI keeps increasing through the summer in the Warm_LAI×2 experiment, LE will continue increasing despite the negative soil moisture anomalies. In response, evident reductions in soil moisture are only found in the arid and semiarid regions (e.g., the Great Plains and the western United States). Although LE has significantly increased in the Midwest and the lower Mississippi River basin (especially during spring), there is little change in soil moisture, as adequate precipitation in these humid regions accounts for increased vegetation water use and LE. In addition, more LE can modify boundary layer conditions, resulting in a more conducive mesoscale environment for convective precipitation (i.e., soil moisture–precipitation feedback). Figure S9 shows increased precipitation in the central United States (including the Midwest and the lower Mississippi River basin), and a particular increase in Texas and northern Mexico during summer with increased LAI. The increased precipitation attributable to soil moisture feedback can also help offset soil moisture reductions from increased vegetation productivity. It should be noted that atmospheric nudging has limited the impacts on teleconnections. Therefore, the increased precipitation is mainly the result of the local impacts of the enhanced evapotranspiration. The positive feedback between evapotranspiration and precipitation is also documented in the previous studies (Chen and Dirmeyer 2017).

d. Impacts of increased LAI on flash drought

With the general understanding of the changes in soil moisture induced by the increased LAI, we examine the impacts on flash drought occurrence (Figs. 5a,b). Similar to the response in soil moisture, evident changes in flash drought occurrence are only found in the Great Plains and the western United States, where vegetation greening may lead to more frequent flash drought. The flash drought occurrence approaches twice that of the Control simulation over those regions. Although there is increased LAI in the eastern United States, the resultant change in flash drought occurrence is small and not significant. Comparing the two sensitivity experiments, the longer vegetation greening during the warm season can make flash drought even more frequent due to the rapid soil dry-out through enhanced ET. Additionally, we explore the possible impacts of vegetation on the ratio of flash drought to all-type drought (Fig. S10). Similar to the changes in flash drought, the number of all-type drought events increases mainly in the Great Plains and the western United States. Increased flash drought ratios are only found in limited areas of the southern Plains and the western United States, indicating more typical drought events would become flash droughts with the influence of vegetation greening over those regions.

Figure 6 shows two examples of flash drought at a grid point in western Oklahoma (35.34°N, 100°W) and a grid point in southern Illinois (39.1°N, 90°W). The flash drought in August 2010 only appears in Warm_LAI×2 (Fig. 6a). Although the Control and Spring_LAI×2 experiments also undergo a gradual drying during this period, the lowest soil moisture does not reach the threshold of our flash drought definition (below the 20th percentile). During the flash drought in 2012, all the experiments exhibit a drying trend since early or mid-May, while the drying is at a more rapid rate in the two increased LAI experiments (Fig. 6b).

Although the main focus of this study is vegetation effects on flash drought occurrence, we also examine the impacts on flash drought duration and extent. Figures 5c and 5d shows the
changes in warm-season (March–September) flash drought duration in response to increased LAI. Except for limited regions in the western United States, vegetation does not exert significant impacts on flash drought duration in most areas of the country. This can be associated with the mechanism of drought development and demise. Although the increased LAI can potentially trigger more flash drought events to onset, drought demise is dominantly influenced by atmospheric factors, such as tropical cyclones and atmospheric rivers, while land–atmosphere feedback only plays a secondary role (Wu and Dirmeyer 2020). In this study, the large-scale circulations are kept consistent among the drought experiments using atmospheric nudging. Therefore, it is expected that the duration of flash drought would not be significantly influenced by vegetation changes.

Figure 7 shows flash drought spatial extent and its response to increased LAI. The area of flash drought is calculated based on the number of grids with flash drought identified for each month of the warm season (March–September) averaged over the period 1979–2014. The increased LAI leads to significantly more areas with flash drought occurrence during the warm season. In the Control experiment, about 32% of the U.S. areas experience flash drought during the warm season. With doubled LAI, there will be an additional 12% of areas undergoing flash drought. The increased area of flash drought can also be supported by the case-study years in Fig. S4.

e. Land–atmosphere coupling

To further understand the response of flash drought to vegetation dynamics, we explore the relationship between LAI, LE, and soil moisture (Fig. 8). Figure 8c shows that there is a positive relationship between the increased LAI and associated changes in LE, and the precipitation conditions clearly regulate the responses of LE to LAI. In the low-precipitation region, LE is more sensitive to the variations of LAI, while in the high-precipitation area, the slope between $\Delta$LAI and $\Delta$LE is relatively flat. This finding agrees with previous studies (Williams and Torn 2015; Forzieri et al. 2018), which suggest that LAI of tree and grass biomes controls the variations in LE, especially in low-precipitation regimes. Meanwhile, we see a clear negative relationship between the variations of LE and that of soil moisture (Fig. 8d), suggesting an increase in LE can lead to negative soil moisture anomalies. Similarly, the stronger coupling is found in the moisture-limited regimes, indicating that the excessive LE would accelerate soil moisture depletion in those regions. Combining the relationships depicted in Fig. 8, we conclude that LAI plays a more important role in warm-season soil moisture...
dynamics over arid and semiarid regions than over the humid regions.

4. Discussion

The first goal of this study is to evaluate the performance of CESM2 in representing flash droughts. It also should be noted that uncertainties exist in the approaches of flash drought identification. This study follows the method used in Ford and Labosier (2017), in which the flash drought is defined based on the temporal evolution of soil moisture. Our results show high flash drought occurrence in the Southeast, which agrees with the flash drought climatology in Ford and Labosier (2017). However, this study also suggests a high flash drought occurrence in the Great Plains. This disagreement might be associated with the different soil moisture products used in drought detection. Other approaches, such as Koster et al. (2019), have included additional constraints on evapotranspiration over the humid and arid regions, and show the highest flash drought frequency in the southern Great Plains. If applying the same constraints to this study, CESM2 can replicate the climatology of flash drought occurrence (Fig. S11) that is identified in Koster et al. (2019). On the other hand, in Christian et al. (2019), flash drought identification is based on the evaporative stress ratio, which suggests the hot spot regions of flash droughts are located in the Great Plains extending into the Corn Belt and western Great Lakes region. Therefore, the criterion and threshold used in flash drought identification can produce somewhat different patterns of the flash drought climatology (Koster et al. 2019). The uncertainties related to flash drought detection approaches are left for future work.

We acknowledge the model uncertainty in representing soil moisture dynamics. There is considerable difference in detected flash drought occurrence between the reanalysis data and CESM2 (Fig. 3), especially over the Midwest. Previous studies have documented the uncertainties of CMIP5 models in soil moisture variability (Yuan and Quiring 2017) and soil moisture drought (Ukkola et al. 2018). We calculate the variability of pentad-average soil moisture during the warm seasons from four datasets (Fig. S12). Clearly, there is a good agreement between soil moisture variability and flash drought occurrence (Fig. 3)—regions with higher soil moisture variability usually have more frequent flash droughts. Although

![Fig. 6. Examples of identified flash droughts in the Control, Spring_LAIx2, and Warm_LAIx2 experiments at (a) a grid point in the western Oklahoma (35.34°N, 100°W) and (b) a grid point in the southern Illinois (39.1°N, 90°W). The horizontal dashed lines represent the 20th and 40th percentiles of soil moisture that are used for flash drought identification. It should be noted that flash drought (FD) is only identified in the Warm_LAIx2 experiment in (a).](image)

![Fig. 7. Average percent of the contiguous U.S. area (25°–50°N, 125°–65°W) with at least one flash drought event during the month or season (March–September) in 1979–2014. The light gray, dark gray, and black bars correspond to the CESM2 control, Spring_LAIx2, and Warm_LAIx2 simulations, respectively. Asterisk signs above the bar indicate that the areas derived from the sensitivity experiments are significantly different from the control experiment based on the Student’s $t$ test ($p < 0.05$). Based on the criteria used in flash drought identification, the minimum flash drought duration is 4 pentads.](image)
the dry bias in CESM2 can be partially responsible for the frequent flash droughts in the Midwest, soil moisture variability (Fig. S12c) and flash drought detection (Christian et al. 2019) from NARR still suggest that this region can be a hot spot for flash drought. According to Fig. S12, it is evident that the uncertainty in simulated soil moisture exists not only in climate models, but also in different reanalysis or observation-driven datasets. Therefore, soil moisture observations are highly needed for future flash drought evaluations, and flash drought analysis based on multimodel experiments [such as the Land Surface, Snow and Soil Moisture Model Intercomparison Project (LS3MIP) in CMIP6; van den Hurk et al. 2016] should be conducted to further quantify the uncertainties among different land surface models.

Another aspect of this study is to investigate the possible impacts of vegetation greening on flash drought occurrence. To isolate the vegetation feedback to drought, we use prescribed values for LAI in the sensitivity experiments. Our results highlight the major contribution of atmospheric circulation to flash droughts. Under similar atmospheric conditions, the prescribed vegetation greening may lead to a higher chance of flash drought. Although the doubled LAI in our sensitivity experiments might be an extreme scenario of vegetation greening, previous studies have documented the global greening (Piao et al. 2020) and earlier greening (Lian et al. 2020) under the background of climate change in recent decades, and the greening will continue in the future. Therefore, the identified vegetation feedback on flash drought in this study also has important implications for drought assessment in future climate.

Moreover, it should be noted that vegetation also reacts to flash droughts in different ways. Soil water stress can lead to decreased stomatal conductance, and thus to reduced transpiration (Hunt et al. 2014). Long-period droughts can lead to a reduction in plant productivity and crop failure (Sun et al. 2015). These physiological variations should be considered in future studies to explore the interactions between vegetation and the atmosphere. As climate projections suggest increasing soil moisture drought conditions in large areas of North America (Berg and Sheffield 2018; Cook et al. 2014), there will likely be an increased risk of flash drought in a warming climate. Although the extensive irrigation over the Great Plains has the potential to mitigate the flash drought risk at local and regional scales, the documented groundwater depletion (Condon and Maxwell 2019) may pose challenges for satisfying irrigation water demands in the future.
5. Conclusions

In this study, we first examine the warm-season (March–September) flash drought occurrence over the United States using a flash drought identification method developed by Ford and Labosier (2017). Based on MERRA-2, NCA-LDAS, and CESM2, a hot spot of flash drought occurrence is found over the central and southeastern United States. With atmospheric nudging, CESM2 exhibits improved performance in representing historical flash drought events (such as the central U.S. flash drought in 2012). However, the model shows high flash drought frequency in the Midwest, which does not appear in the reanalysis and observation-based datasets.

A set of sensitivity experiments in CESM2 are used to explore the impacts of vegetation greening on flash drought occurrence. Compared to the Control simulation with actual LAI, the sensitivity experiments with doubled LAI in March–May and March–August show significantly increased flash drought frequency in the Great Plains and the western United States due to enhanced evapotranspiration that would accelerate soil moisture depletion. Flash drought frequency can increase up to about twice of the values in the Control simulation. However, flash drought occurrence is not sensitive to vegetation dynamics in the eastern United States and the Midwest due to relatively weak land–atmosphere coupling. Additionally, we found that the areas with warm-season flash drought occurrence also increase after vegetation greening, but the duration of flash drought is not sensitive to the vegetation change. Our results highlight the importance of vegetation phenology in flash drought development. In the regions with strong land–atmosphere coupling, springtime vegetation can play a role in soil moisture conditions during summer through soil moisture memory. Therefore, it is necessary to take into account the vegetation condition for warm-season flash drought monitoring and early warning.

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