https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

Hydrology and Earth System Sciences
Discussions
Open Access

Rapid reduction in ecosystem productivity caused by flash drought based on decade-long FLUXNET observations

Miao Zhang[a,c], Xing Yuan[b*]

[a]Key Laboratory of Regional Climate-Environment for Temperate East Asia (RCE-TEA), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China

[b]School of Hydrology and Water Resources, Nanjing University of Information Science and Technology, Nanjing 210044, China

[c]College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing 100049, China

[*]*Corresponding author address:* Xing Yuan, School of Hydrology and Water Resources, Nanjing University of Information Science and Technology, Nanjing 210044, China E-mail: xyuan@nuist.edu.cn

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

Hydrology and Earth System Sciences
Discussions

Abstract. Flash drought is characterized by its rapid onset and arouses wide concerns due to its devastating impacts on the environment and society without sufficient early warnings. The increasing frequency of flash drought in a warming climate highlights the importance of understanding its impact on terrestrial ecosystems. Previous studies investigated the vegetation dynamics during several extreme cases of flash drought, but there is no quantitative assessment on how fast the carbon fluxes respond to flash drought based on decade-long records with different climates and vegetation conditions. Here we identify flash drought events by considering decline rate of soil moisture and the drought persistency, and detect the response of ecosystem carbon and water fluxes to flash drought during its onset and recovery stages based on observations at 34 FLUXNET stations from grasslands to forests. Corresponding to the sharp decline in soil moisture, gross primary productivity (GPP) drops below its normal conditions in the first 16 days and reduces to its minimum within 24 days for more than 50% of the 165 identified flash drought events, and savannas show highest sensitivity to flash drought. Water use efficiency increases for forests but decreases for cropland and savanna during the recovery stage of flash droughts. These results demonstrate the rapid responses of vegetation productivity and physiological adaptation for forest ecosystems to flash drought.

Keywords: Flash drought; GPP; Soil moisture; Water use efficiency; FLUXNET

1. Introduction

Terrestrial ecosystems play a key role in the global carbon cycle and absorb about 30% of anthropogenic carbon dioxide emissions during the past five decades (Le Quéré et al., 2018). With more climate extremes (e.g. drought, heat wave) in a warming climate, the rate of land carbon uptake is highly uncertain regardless of the fertilization effect of rising atmospheric carbon dioxide (Green et al., 2019; Reichstein et al., 2013; Xu et al., 2019). Terrestrial ecosystems can even turn to carbon source in some extreme drought events (Ciais et al., 2005). Record-breaking drought events have caused enormous reduction of the ecosystem gross primary productivity (GPP), such as the European 2003 drought (Ciais et al., 2005; Reichstein et al., 2007), USA 2012 drought (Wolf et al., 2016), China 2013 drought (Xie et al., 2016; Yuan et al., 2016), Southern Africa 2015/16 drought (Yuan et al., 2017) and Australia Millennium drought (Banerjee et al., 2013). The 2012 summertime drought in USA was classified as flash drought with rapid intensification and insufficient early warning, which caused 26% reduction in crop yield (Hoerling et al., 2014; Otkin et al., 2016). Flash drought has aroused wide concerns for its unusually rapid development and detrimental effects (Basara et al., 2019; Christian et al., 2019; Ford & Labosier, 2017; Nguyen et al., 2019; Otkin et al., 2018; Yuan et al., 2015; Yuan et al., 2017; Yuan et al., 2019b). Despite the increasing occurrence and clear ecological impacts of flash droughts, our understanding of their impacts on carbon uptake in terrestrial ecosystems remains incomplete.

Recent studies assessed the impact of flash drought on vegetation including the

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

2012 central USA flash drought and the 2017 northern USA flash drought. For instance, Otkin et al. (2016) used the evaporative stress index (ESI) to detect the onset of the 2012 central USA flash drought, and found the decline in ESI preceded the drought according to the United States Drought Monitor. He et al. (2019) assessed the impacts of the 2017 northern USA flash drought on vegetation productivity based on GOME-2 solar-induced fluorescence (SIF) and satellite-based evapotranspiration in the US Northern plains. Otkin et al. (2019) examined the evolution of vegetation conditions using LAI from MODIS during the 2015 flash drought over the South-Central United States and found that the LAI decreased after the decline of soil moisture. However, previous impact studies only focused on a few extreme flash drought cases without explicit definition of flash drought events. As the baseline climate is changing (Yuan et al., 2019b), it is necessary to systematically investigate the response of terrestrial carbon and water fluxes to flash drought events based on long-term records rather than one or two extreme cases.

In fact, there are numerous studies on the influence of drought on ecosystem productivity (Ciais et al., 2005; Stocker et al., 2018; Stocker et al., 2019). It is found that understanding the coupling of water-carbon fluxes during drought is the key to revealing the adaptation and response mechanisms of vegetation to water stress (Boese et al., 2019; Nelson et al., 2018). Water use efficiency (WUE) is the metric for understanding the trade-off between carbon assimilation and water loss through transpiration (Beer et al., 2009; Cowan and Farquhar, 1977; Zhou et al., 2014, 2015), and it is influenced by environmental factors including atmospheric dryness and soil

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

moisture limitations (Boese et al., 2019). Although WUE has been widely studied for seasonal to decadal droughts, few studies have investigated WUE during flash droughts that usually occur at sub-seasonal time scale.

In this paper, we address the ecological impact of flash droughts through analyzing FLUXNET decade-long observations of CO_2 and water fluxes. The specific goals are to (1) examine the response of carbon and water fluxes to flash droughts from the onset to the recovery stages, and (2) investigate how WUE changes during flash drought for different ecosystems. The methodology proposed by Yuan et al. (2019b) enables the analysis of the flash drought with characteristics of duration, frequency, and intensity in the historical observations. All the flash drought events occurred at the FLUXNET stations are selected to investigate the response of carbon fluxes and WUE. More than 10-year records of soil moisture, carbon and water fluxes are available (Baldocchi et al., 2002), which makes it possible to assess the response of vegetation to flash droughts by considering different climates and ecosystem conditions.

2. Data and Methods

2.1 Data

FLUXNET2015 provides daily hydrometeorological variables including precipitation, temperature, saturation vapor pressure deficit (VPD), soil moisture (sm), evapotranspiration (ET) inferred from latent heat, and carbon fluxes including GPP. We use GPP data based on night-time partitioning method (GPP_NT_VUT_REF). Considering most sites only measure the surface soil moisture, here we use daily soil

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

moisture measurements mainly at the depth of 5-10 cm averaged from half-hourly data. All daily hydrometeorological variables and carbon fluxes are summed to 8-day time scale to study the flash drought impact. We select 34 sites from FLUXNET 2015 dataset (Table 1), where the periods of observations are no less than 10 years ranging from 1996 to 2014, and the rates of missing data are lower than 5%. The FLUXNET observations include 12 evergreen needleleaf forest sites (ENF), 5 deciduous broadleaf forests (DBF) and 6 crop sites (CROP; 5 rain-fed sites and 1 irrigated site) etc. The detailed information is listed in Table 1. Here we select three flash drought cases at different ecosystems including ENF (FI-Sod site), savanna (SAV; US-SRM site) and DBF (IT-Col site) to show the response of vegetation to flash droughts.

2.2 Methods

2.2.1 Definition of flash drought events

The definition of flash drought should account for both its rapid intensification and the drought conditions (Otkin et al., 2018; Yuan et al., 2019b). Here we used soil moisture percentile to identify flash drought according to Yuan et al. (2019b) and Ford et al. (2017). Figure 1 shows the procedure for flash drought identification, including five criteria to identify the rapid onset and recovery stages of flash drought. 1) Flash drought starts when the 8-day mean soil moisture is less than the 40th percentile, and the 8-day mean soil moisture prior to the starting time should be higher than 40th percentile to ensure the transition from a non-drought condition. 2) The mean decreasing rate of 8-day mean soil moisture percentile should be no less than 5% to address the rapid drought intensification. 3) The 8-day mean soil moisture after the rapid decline should be less than 20% in percentile, and the period from the beginning to the end of the rapid decline is regarded as the onset stage of flash drought (those within red dashed line in Figure 1). 4) If the mean decreasing rate is less than 5% in percentile or the soil moisture percentile starts to increase, the flash drought enters into the "recovery" stage, and the flash drought event (as well as the recovery stage) ends when soil moisture recovers to above 20th percentile (those within blue dashed line in Figure 1). The recovery stage is also crucial to assess the impact of flash drought (Yuan et al., 2019b). 5) The minimum duration of a flash drought event is 24 days to exclude those dry spells that last for a too short period to cause any impacts, and the maximum duration is limited to 2 months to separate flash droughts from traditional droughts (e.g., seasonal droughts).

Decade-long observations of 8-day mean soil moisture are used to calculate soil moisture percentile with a moving window of 8-day before and 8-day after the target 8-day, resulting in at least 30 samples for deriving the cumulative distribution function of soil moisture before calculating percentiles. For example, the soil moisture percentile of June 22nd in 1998 is calculated by firstly ranking June 14th, June 22nd, and June 30th soil moisture in all historical years (N samples) from lowest to highest, identifying the rank of soil moisture of June 22nd, 1998 (e.g., M), and obtaining the percentile as M/N*100. We focus on growing seasons during April-September for sites in the North Hemisphere and October-March for sites in the South Hemisphere.

2.2.2 Response time of GPP to flash drought

Drought has a large influence on ecosystem productivity through altering the plant

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

photosynthesis and ecosystem respiration (Beer et al., 2010; Green et al., 2019; Heimann & Reichstein, 2008; Stocker et al., 2018). GPP dominates the global terrestrial carbon sink and it would decrease due to stomatal closure and non-stomatal limitations like reduced carboxylation rate and reduced active leaf area index (de la Motte et al., 2019) under water stress. The negative anomalies of GPP during flash drought are considered as the signal of ecological deterioration. Here, we use two response time indices to investigate the relationship between flash drought and ecological drought (Niu et al., 2018; Song et al., 2018; Vicente-Serrano et al., 2013): 1) the response time of the first occurrence of negative standardized GPP anomaly (SGPPA=$\frac{GPP-\mu_{GPP}}{\sigma_{GPP}}$, where μ_{GPP} and σ_{GPP} are mean and standard deviation of the time series of GPP at the same dates as the target 8-days for all years, which can remove the influence of seasonality. For instance, all Apr 1-8 during 1996-2014 would have a μ_{GPP} and a σ_{GPP}, and Apr 9-16 would have another μ_{GPP} and another σ_{GPP}, and so on), which is the lag time between the start of flash drought and the time when SGPPA becomes negative during flash drought period; and 2) the response time of occurrence of minimum SGPPA, which is the lag time between the start of flash drought and the time when SGPPA decreases to its minimum values during the flash drought period. If the response time is 8 days for the first occurrence of negative SGPPA, it means that the response of GPP starts at the beginning of flash drought (the first time step of flash drought).

2.2.3 Water use efficiency

Carbon assimilation and transpiration are coupled by stomates under the influence of water and energy conditions (Boese et al., 2019; Huang et al., 2016; Nelson et al., 2018). Plants face a tradeoff at the level of the stomata to fix carbon through photosynthesis at the cost of water losses through transpiration. WUE quantifies the trade-off, which is defined as the assimilated amount of carbon per unit of water loss. At the ecosystem scale, WUE is the ratio of GPP over ET (Cowan and Farquhar, 1977). Drought would cause stomatal closure and non-stomatal adjustments in biochemical functions thus altering the coupling between GPP and ET. Underlying WUE (uWUE) is calculated as $\mathrm{GPP} \times \sqrt{VPD}/ET$ considering the nonlinear relationship between GPP, VPD and ET (Zhou et al., 2014). uWUE is supposed to reflect the relationship of photosynthesis-transpiration via stomatal conductance at the ecosystem level by considering the effect of VPD on WUE (Beer et al., 2009; Boese et al., 2019; Zhou et al., 2014, 2015). WUE varies under the influence of VPD on canopy conductance (Beer et al., 2009; Tang et al., 2006), whereas uWUE is considered to remove this effect and be more directly linked with the relationship between environmental conditions (e.g., soil moisture) and plant conditions (e.g., carboxylation rate; Lu et al., 2018). The standardized anomalies of WUE and uWUE are calculated the same as SGPPA, where different sites have different mean values and standard deviations for different target 8-days to remove the spatial and temporal inhomogeneity.

3. Results

3.1 Identification of flash drought events at FLUXNET stations

Based on FLUXNET data, we have identified 165 flash drought events with

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

durations longer than 24 days using soil moisture observations of 428 site years. Figure 2a shows the distribution of the 34 sites with different vegetation types. The number of flash drought ranged from 1 to 12 events among FLUXNET sites, and the mean durations were from around 30 days to 60 days among FLUXNET sites (Figures 2b and 2c). The frequency of flash drought shows great spatial heterogeneity which may be associated with variability of soil moisture. If enough rainfall comes after the flash drought, the soil moisture could recover to above 20% percentile. Without enough rainfall for recovery, flash drought would ultimately develop into longer and more severe drought (Wang and Yuan, 2018).

Figure 3 shows the standardized anomalies of temperature, precipitation, VPD, and ET during different stages of flash drought. There is a slight reduction in precipitation and increase in ET during 8 days prior to flash drought (Figure 3b&d). During the onset of flash drought, the rapid drying of soil moisture is always associated with a large precipitation deficits, and anomalously high temperature and large VPD indicate increased atmospheric dryness (Ford et al., 2017; Koster et al., 2019; Wang et al., 2016), which persist until the recovery stage. ET is close to normal conditions thus enhancing the drying rate of soil moisture with less precipitation supply during the onset stage (Figure 3b&d). However, ET starts to decrease during the recovery stage because of the limitation from water availability, which alleviates the drought condition. Sufficient precipitation occurs during the 8 days after flash droughts to relieve the drought condition.

3.2 Evolutions of carbon and water fluxes during flash drought events

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

Hydrology and Earth System Sciences Discussions
Open Access
EGU

Figure 4 shows the evolutions of soil moisture percentile, standardized GPP and ET anomalies during the flash droughts occurred in 2003 at FI-Sod site (Ciais et al., 2005), 2004 at US-SRM site and 2007 at IT-Col site.

FI-Sod is covered by northern boreal Scots pine with mean annual temperature of -1℃(Thum et al., 2007). 2003 summer drought over Europe accompanied by heat wave caused enormous carbon losses with 30% reduction in GPP (Ciais et al., 2005), and the drought outweighed heat wave for influencing the ecosystem (Reichstein et al., 2007). The 2003 flash drought at FI-Sod occurred in the late of June and ended in the early July although the soil moisture condition was still below the climatology (Figure 4a). During the 24-day flash drought, GPP and ET respond quickly to the rapid soil moisture drying and recover to their normal conditions as soon as the drought relieves (Figures 4b and 4c), which shows the resilience of evergreen needleleaf forest to short-term drought. Negative ET anomaly (Figure 4c) precedes the onset of soil moisture drought, indicating that the flash drought is mainly caused by rainfall deficit (Figure 4a).

US-SRM site is in dry land savanna. Savanna covers 20% of the global land area (Sankaran et al., 2005), and influences the terrestrial carbon sink significantly (Ahlstrom et al., 2015). Soil moisture plays a crucial role in regulating carbon and water fluxes in savanna regions (Scott et al., 2009; Williams & Albertson, 2004; Wolf et al., 2016), and there is a large variability of soil moisture at US-SRM. Soil moisture percentile declined from 33% to 5% in 8 days and stayed below 20% for 8 days (Figure 4d). The rapid decline in soil moisture is mainly from rainfall deficits because

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

the evapotranspiration process is limited by soil water in semiarid savanna region. GPP and ET both decrease with the decline in soil moisture (Figures 4e and 4f), and the negative anomalies persist even after the flash drought. As there is not enough rainfall to alleviate soil moisture drought, the vegetation damage continues (Figure 4e).

The flash drought lasted for 56 days in 2007 at IT-Col site and propagated into a long-term drought due to the persistence of precipitation deficits. IT-Col is in deciduous broadleaf forest with relatively humid climate (Van Dijk & Dolman, 2004). There is a lag time of 8 days between the responses of GPP and ET to flash drought (Figures 4h and 4i), which is because that the positive evapotranspiration anomaly at the onset of flash drought (30^{th} in June) is driven by higher temperature and VPD. GPP and ET are below the climatology during flash drought, indicating the degradation in vegetation under water stress. The whole reduction of ET during flash drought is relatively small compared with GPP, indicating the decoupling between water and carbon fluxes.

In short, both GPP and ET fluxes reduce rapidly in responding to the sharp decline in soil moisture, although the reduction depends on environmental conditions and vegetation characteristics (Vicente-Serrano et al., 2013).

3.3 Climatological statistics of the response time of GPP to flash drought

By analyzing all the 165 flash drought events across 34 FLUXNET sites, we find that negative GPP anomalies occur during 81% of the flash drought events. Figures 5a and 5b show the probability distributions of the response time of GPP to flash drought

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

Hydrology and Earth System Sciences
Discussions
Open Access

for the first occurrence of negative SGPPA and the minimum negative value of SGPPA, respectively. The first occurrences of negative SGPPA are concentrated during the first 24 days, and for 57% flash droughts, GPP starts to respond to flash drought within 16 days (Figure 5a). The occurrences of minimum value of SGPPA rise sharply at the beginning of flash drought, and reach the peak during 17-24 days, and then slow down (Figure 5b), which is similar to the decline in soil moisture. Although the first occurrences of negative SGPPA mainly occur in onset stage, GPP would continue to decrease in recovery stages for 60% of flash drought events. The time for soil moisture reaching its minimum is concentrated during 9-16 days since the occurrence of flash drought, preceding the minimum GPP by about 8 days. Large decreases in soil moisture percentiles are during the first 16 days of flash drought (Figure 5c), while large decrease in GPP occurs during 9-24 days (Figure 5d).

Different types of vegetation including herbaceous plants and woody plants all react to flash drought in the early stage (Figures 6). Among them, savanna shows the fastest reaction to water stress (Figure 6a&6f), with 63% events showing vegetation response concurrently with flash drought onset and ultimately 88% events showing impaired vegetation photosynthesis. The result is consistent with the high vulnerability of vegetation in semiarid regions (Vicente-Serrano et al., 2013; Zeng et al., 2018). The decline rates in soil moisture show differences among different vegetation types during flash drought, which are related to soil texture, vegetation cover and climates.

3.4 WUE under soil moisture stress

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

Figure 7 shows the standardized anomalies of WUE and uWUE and their components for different ecosystems during the onset and recovery stages of flash drought. Evergreen broadleaf forest (EBF) and grassland (GRA) were excluded due to insufficient flash drought cases. Here, we select 81% of flash drought events with GPP declining down to its normal conditions to analyze the interactions between carbon and water fluxes. WUE is stable during the onset stage except for croplands and mixed forests (MF), whereas uWUE increases for all ecosystems (Figure 7a). For croplands, both GPP and ET decrease, and the decline in WUE is related with a greater reduction in GPP relative to ET (Figure 7c&e). The positive anomalies of uWUE are correlated with decrease in $ET/\sqrt{VPD}$ mainly induced by the high VPD. Increasing VPD and deficits in soil moisture would decrease canopy conductance (Grossiord et al., 2020) but not GPP for MF and ENF. During the onset stage, GPP and ET reduce only for savannas, croplands, and DBF, and the magnitudes of GPP and ET reduction are highest for savannas. But for recovery stage, GPP and ET show significant reductions except for MF, and the responses of WUE and uWUE are different between herbaceous plants (savannas and croplands) and forests (MF, DBF, and ENF), where WUE and uWUE decrease significantly for savannas and croplands but increase slightly for forests (Figure 7b). The decrease in GPP during recovery stage is not only related to the reduction in canopy conductance, but also the decrease in uWUE under drought for savannas and croplands which is possibly influenced by suppressed state of enzyme and reduced mesophyll conductance (Flexas et al., 2012). The average soil moisture conditions are 11% in percentile for recovery stage but 18%

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

for onset stage. So, drier soil moisture in the recovery stage exacerbates ecological response. Figure 7b also shows the higher WUE and uWUE for forests, which indicates their higher resistance to flash drought than herbaceous plants during recovery stage.

4. Discussion

Previous studies detected the vegetation response for a few extreme drought cases without a specific definition of flash drought from a climatological perspective (Otkin et al., 2016; He et al., 2019). Moreover, less attention has been paid to the coupling between carbon and water fluxes during flash drought events. This study investigates the response of carbon and water fluxes to flash drought based on decade-long FLUXNET observations. The responses vary across different phases of flash drought, and different ecosystems have different responses, which provide implications for eco-hydrological modeling and prediction.

4.1 The responses of carbon and water fluxes to flash droughts

Based on 165 flash drought events identified using soil moisture from decade-long FLUXNET observations, the response of GPP to flash drought is found to be quite rapid. For more than half of the 165 flash drought events, the GPP drops below its normal conditions during the first 16 days and reaches its maximum intensity within 24 days. Eventually, 81% of flash drought events cause negative ecological impacts on GPP. During the drought period, plants would close their stomata to minimize water loss through decreasing canopy conductance, which in turn leads to a reduction in carbon uptake. High VPD further reduces canopy conductance

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

during flash drought. The suppression of GPP and ET is more obvious for flash drought recovery stage than the onset stage. The discrepancy of GPP responses between different phases of flash drought may result from 1) soil moisture conditions which are drier during the recovery stage, and 2) the damaged physiological functioning for specific vegetation types. The anomalies of uWUE for ecosystems are always positive or unchanged during flash drought except for croplands and savannas during recovery stage. The decrease in canopy conductance would limit photosynthetic rate, however, the increase of uWUE indicates adaptative regulations of ecosystem physiology which is consistent with Beer et al. (2009). uWUE is higher than WUE during onset stage of flash drought, which is due to the decreased conductance under increased VPD. However, there is no obvious difference between WUE and uWUE during recovery stage, which indicates that photosynthesis is less sensitive to stomatal conductance and may be more correlated with limitations of biochemical capacity (Flexas et al., 2012; Grossiord et al., 2020).

This study is based on the sites that are mainly distributed over North America and Europe. It is necessary to investigate the impact of flash drought on vegetation over other regions with different climates and vegetation conditions. In addition, this study used in-situ surface soil moisture at FLUXNET stations to detect vegetation response due to the lack of soil moisture observations at deep soil layers. There would be more significant ecological responses to flash drought identified through using root-zone soil moisture because of its close link with vegetation dynamics.

4.2 Variation in ecological responses across vegetation types

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

The responses of GPP, ET and WUE to flash drought vary among different vegetation types. The decline in GPP and ET only occurs across croplands and savannas during onset stage. For most forests, the deterioration of photosynthesis and ET appears during the recovery stage with higher WUE and uWUE. For croplands and savannas, both WUE and uWUE decrease during the recovery stage. The positive anomalies of WUE and uWUE for forests show the adaptation of vegetation to flash drought from physiological perspective. Xie et al. (2016) pointed out that WUE and uWUE for a subtropical forest increased during the 2013 summer drought in southern China. The increased WUE in forest sites and unchanged WUE in grasslands were also found in other studies for spring drought (Wolf et al., 2013). In general, herbaceous plants are more sensitive to flash drought than forests, especially for savannas.

4.3 Potential implications for ecosystem modelling

The study reveals the profound impact of flash droughts on ecosystem through analyzing eddy covariance observations. It is found that the responses of carbon and water exchanges are quite distinguishing for forests and herbaceous plants. For the ecosystem modeling, the response of stomatal conductance under soil moisture stress has been addressed in previous studies (Wilson et al., 2000), but there still exists deficiency to capture the impacts of water stress on carbon uptake (Keenan et al., 2009), which is partly due to the different responses across species. Incorporating physiological adaptations to drought in ecosystem modeling especially for forests would improve the simulation of the impact of drought on the terrestrial ecosystems.

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

5. Conclusion

This study presents how carbon and water fluxes respond to flash drought during onset and recovery stages through analyzing decade-long observations from FLUXNET. Ecosystems show high sensitivity of GPP to flash drought especially for savannas, and GPP starts to respond to flash droughts within 16 days for more than half of the flash drought events. However, the responses of WUE and uWUE vary across vegetation types. Positive WUE and uWUE anomalies for forests during the recovery stage indicate the physiological adaptation to flash drought through non-stomatal regulations, whereas WUE and uWUE decrease for croplands and savannas during the recovery stage. For now, the main concern about the ecological impact of flash drought is concentrated on the period of flash drought and the legacy effects of flash drought are not involved. It still needs more efforts to study the subsequent effects of flash droughts which would contribute to assessing the accumulated ecological impacts of flash drought. Nevertheless, this study highlights the rapid response of vegetation productivity to soil moisture dynamics at sub-seasonal timescale, and different responses of water use efficiency across ecosystems during the recovery stage of flash droughts, which complements previous studies on the sensitivity of vegetation to extreme drought at longer time scale. Understanding the response of carbon fluxes and the coupling between carbon and water fluxes to drought might help assessing the resistance and resilience of vegetation to drought.

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

Hydrology and Earth System Sciences Discussions

Acknowledgements

This work was supported by National Natural Science Foundation of China (41875105), National Key R&D Program of China (2018YFA0606002) and the Startup Foundation for Introducing Talent of NUIST. The data used in this study are all from FLUXNET 2015 (https://fluxnet.fluxdata.org/data/fluxnet2015-dataset/).

Data availability statement

Carbon fluxes and hydrometeorological variables from FLUXNET2015 are available through https://fluxnet.fluxdata.org/data/fluxnet2015-dataset/.

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

References

Atjay, G. L., Ketner, P. and Duvigneaud, P.: Terrestrial primary production and phytomass, in The Global Carbon Cycle: SCOPE 13, John Wiley, Hoboken, N. J., 129–182, 1979

Ahlstrom, A., Raupach, M. R., Schurgers, G., Smith, B., Arneth, A., Jung, M., Reichstein, M., Canadell, J. G., Friedlingstein, P., Jain, A. K., Kato, E., Poulter, B., Sitch, S., Stocker, B. D., Viovy, N., Wang, Y. P., Wiltshire, A., Zaehle, S. and Zeng, N.: The dominant role of semi-arid ecosystems in the trend and variability of the land CO_2 sink, Science, 348(6237), 895–899, https://doi.org/10.1126/science.aaa1668, 2015.

Baldocchi, D., Wilson, K., Valentini, R., Law, B., Munger, W., Davis, K., Wofsy, S., Pilegaard, K., Goldstein, A., Falge, E., Vesala, T., Hollinger, D., Running, S., Fuentes, J., Katul, G., Gu, L., Verma, S., Paw, K. T., Malhi, Y., Anthoni, P., Oechel, W., Schmid, H. P., Bernhofer, C., Meyers, T., Evans, R., Olson, R. and Lee, X.: FLUXNET: A New Tool to Study the Temporal and Spatial Variability of Ecosystem–Scale Carbon Dioxide, Water Vapor, and Energy Flux Densities, Bull. Am. Meteorol. Soc., 82(11), 2415–2434, https://doi.org/10.1175/1520-0477, 2002.

Banerjee, O., Bark, R., Connor, J. and Crossman, N. D.: An ecosystem services approach to estimating economic losses associated with drought, Ecol. Econ., 91, 19–27, https://doi.org/10.1016/j.ecolecon.2013.03.022, 2013.

Basara, J. B., Christian, J. I., Wakefield, R. A., Otkin, J. A., Hunt, E. H. H. and Brown,

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

Hydrology and Earth System Sciences Discussions
Open Access

D. P.: The evolution, propagation, and spread of flash drought in the Central United States during 2012, Environ. Res. Lett., 14(8), https://doi.org/10.1088/1748-9326/ab2cc0, 2019.

Beer, C., Ciais, P., Reichstein, M., Baldocchi, D., Law, B. E., Papale, D., Soussana, J. F., Ammann, C., Buchmann, N., Frank, D., Gianelle, D., Janssens, I. A., Knohl, A., Köstner, B., Moors, E., Roupsard, O., Verbeeck, H., Vesala, T., Williams, C. A. and Wohlfahrt, G.: Temporal and among-site variability of inherent water use efficiency at the ecosystem level, Global Biogeochem. Cycles, 23(2), 1–13, https://doi.org/10.1029/2008GB003233, 2009.

Beer, C., Reichstein, M., Tomelleri, E., Ciais, P., Jung, M., Carvalhais, N., Rödenbeck, C., Arain, M. A., Baldocchi, D., Bonan, G. B., Bondeau, A., Cescatti, A., Lasslop, G., Lindroth, A., Lomas, M., Luyssaert, S., Margolis, H., Oleson, K. W., Roupsard, O., Veenendaal, E., Viovy, N., Williams, C., Woodward, F. I. and Papale, D.: Terrestrial gross carbon dioxide uptake: Global distribution and covariation with climate, Science, 329(5993), 834–838, https://doi.org/10.1126/science.1184984, 2010.

Boese, S., Jung, M., Carvalhais, N., Teuling, A. J. and Reichstein, M.: Carbon-water flux coupling under progressive drought, Biogeosciences, 16(13), 2557–2572, https://doi.org/10.5194/bg-16-2557-2019, 2019.

Cowan, I. R. and Farquhar, G. D.: Stomatal function in relation to leaf metabolism and environment, in Integration of Activity in the Higher Plant, edited by D. H. Jennings, Cambridge Univ. Press, Cambridge, U. K., 471–505, 1977

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

Christian, J. I., Basara, J. B., Otkin, J. A., Hunt, E. D., Wakefield, R. A., Flanagan, P. X. and Xiao, X.: A methodology for flash drought identification: Application of flash drought frequency across the United States, J. Hydrometeorol., 20(5), 833–846, https://doi.org/10.1175/JHM-D-18-0198.1, 2019.

Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, C., Carrara, A., Chevallier, F., De Noblet, N., Friend, A. D., Friedlingstein, P., Grünwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J. M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J. F., Sanz, M. J., Schulze, E. D., Vesala, T. and Valentini, R.: Europe-wide reduction in primary productivity caused by the heat and drought in 2003, Nature, 437(7058), 529–533, https://doi.org/10.1038/nature03972, 2005.

de la Motte, L. G., Beauclaire, Q., Heinesch, B., Cuntz, M., Foltýnová, L., Šigut, L., Kowalska, N., Manca, G., Ballarin, I. G., Vincke, C., Roland, M., Ibrom, A., Lousteau, D., Siebicke, L. and Longdoz, B.: Non-stomatal processes reduce gross primary productivity in temperate forest ecosystems during severe edaphic drought, Philos. Trans. R. Soc. B, https://doi.org/10.1098/RSTB-2019-0527, 2019.

Flexas, J., Barbour, M. M., Brendel, O., Cabrera, H. M., Carriquí, M., Díaz-Espejo, A., Douthe, C., Dreyer, E., Ferrio, J. P., Gago, J., Gallé, A., Galmés, J., Kodama, N., Medrano, H., Niinemets, Ü., Peguero-Pina, J. J., Pou, A., Ribas-Carbó, M., Tomás, M., Tosens, T. and Warren, C. R.: Mesophyll diffusion conductance to

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

CO2: An unappreciated central player in photosynthesis, Plant Sci., 193–194, 70–84, https://doi.org/10.1016/j.plantsci.2012.05.009, 2012.

Ford, T. W. and Labosier, C. F.: Meteorological conditions associated with the onset of flash drought in the Eastern United States, Agric. For. Meteorol., 247(April), 414–423, https://doi.org/10.1016/j.agrformet.2017.08.031, 2017.

Ford, T. W., McRoberts, D. B., Quiring, S. M. and Hall, R. E.: On the utility of in situ soil moisture observations for flash drought early warning in Oklahoma, USA, Geophys. Res. Lett., 42(22), https://doi.org/10.1002/2015GL066600, 2015.

Green, J. K., Seneviratne, S. I., Berg, A. M., Findell, K. L., Hagemann, S., Lawrence, D. M. and Gentine, P.: Large influence of soil moisture on long-term terrestrial carbon uptake, Nature, 565(7740), 476–479, https://doi.org/10.1038/s41586-018-0848-x, 2019.

Grossiord, C., Buckley, T. N., Cernusak, L. A., Novick, K. A., Poulter, B., Siegwolf, R. T. W., Sperry, J. S. and McDowell, N. G.: Plant responses to rising vapor pressure deficit, New Phytol., https://doi.org/10.1111/nph.16485, 2020.

He, M., Kimball, J. S., Yi, Y., Running, S., Guan, K., Jensco, K., Maxwell, B. and Maneta, M.: Impacts of the 2017 flash drought in the US Northern plains informed by satellite-based evapotranspiration and solar-induced fluorescence, Environ. Res. Lett., 14(7), 074019, https://doi.org/10.1088/1748-9326/ab22c3, 2019.

Heimann, M. and Reichstein, M.: Terrestrial ecosystem carbon dynamics and climate feedbacks, Nature, 451(7176), 289–292, https://doi.org/10.1038/nature06591,

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

2008.

Hoerling, M., Eischeid, J., Kumar, A., Leung, R., Mariotti, A., Mo, K., Schubert, S. and Seager, R.: Causes and predictability of the 2012 great plains drought, Bull. Am. Meteorol. Soc., 95(2), 269–282, https://doi.org/10.1175/BAMS-D-13-00055.1, 2014.

Huang, M., Piao, S., Zeng, Z., Peng, S., Ciais, P., Cheng, L., Mao, J., Poulter, B., Shi, X., Yao, Y., Yang, H. and Wang, Y.: Seasonal responses of terrestrial ecosystem water-use efficiency to climate change, Glob. Chang. Biol., 22(6), 2165–2177, https://doi.org/10.1111/gcb.13180, 2016.

Keenan, T., García, R., Friend, A. D., Zaehle, S., Gracia, C. and Sabate, S.: Improved understanding of drought controls on seasonal variation in mediterranean forest canopy CO2 and water fluxes through combined in situ measurements and ecosystem modelling, Biogeosciences, 6(8), 1423–1444, https://doi.org/10.5194/bg-6-1423-2009, 2009.

Koster, R. D., Schubert, S. D., Wang, H., Mahanama, S. P. and DeAngelis, A. M.: Flash Drought as Captured by Reanalysis Data: Disentangling the Contributions of Precipitation Deficit and Excess Evapotranspiration, J. Hydrometeorol., 20(6), 1241–1258, https://doi.org/10.1175/jhm-d-18-0242.1, 2019.

Nelson, J. A., Carvalhais, N., Migliavacca, M., Reichstein, M. and Jung, M.: Water-stress-induced breakdown of carbon-water relations: Indicators from diurnal FLUXNET patterns, Biogeosciences, 15(8), 2433–2447, https://doi.org/10.5194/bg-15-2433-2018, 2018.

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

Nguyen, H., Wheeler, M. C., Otkin, J. A., Cowan, T., Frost, A. and Stone, R.: Using the evaporative stress index to monitor flash drought in Australia, Environ. Res. Lett., 14(6), https://doi.org/10.1088/1748-9326/ab2103, 2019.

Niu, J., Chen, J., Sun, L. and Sivakumar, B.: Time-lag effects of vegetation responses to soil moisture evolution: a case study in the Xijiang basin in South China, Stoch. Environ. Res. Risk Assess., 32(8), 2423–2432, https://doi.org/10.1007/s00477-017-1492-y, 2018.

Otkin, J. A., Anderson, M. C., Hain, C., Mladenova, I. E., Basara, J. B. and Svoboda, M.: Examining Rapid Onset Drought Development Using the Thermal Infrared–Based Evaporative Stress Index, J. Hydrometeorol., 14(4), 1057–1074, https://doi.org/10.1175/JHM-D-12-0144.1, 2013.

Otkin, J. A., Anderson, M. C., Hain, C., Svoboda, M., Johnson, D., Mueller, R., Tadesse, T., Wardlow, B. and Brown, J.: Assessing the evolution of soil moisture and vegetation conditions during the 2012 United States flash drought, Agric. For. Meteorol., 218–219, 230–242, https://doi.org/10.1016/j.agrformet.2015.12.065, 2016.

Otkin, J. A., Svoboda, M., Hunt, E. D., Ford, T. W., Anderson, M. C., Hain, C. and Basara, J. B.: Flash droughts: A review and assessment of the challenges imposed by rapid-onset droughts in the United States, Bull. Am. Meteorol. Soc., 99(5), 911–919, https://doi.org/10.1175/BAMS-D-17-0149.1, 2018.

Otkin, J. A., Zhong, Y., Hunt, E. D., Basara, J., Svoboda, M., Anderson, M. C. and Hain, C.: Assessing the Evolution of Soil Moisture and Vegetation Conditions

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

during a Flash Drought–Flash Recovery Sequence over the South-Central United States, J. Hydrometeorol., 20(3), 549–562, https://doi.org/10.1175/jhm-d-18-0171.1, 2019.

Quéré, C., Andrew, R., Friedlingstein, P., Sitch, S., Hauck, J., Pongratz, J., Pickers, P., Ivar Korsbakken, J., Peters, G., Canadell, J., Arneth, A., Arora, V., Barbero, L., Bastos, A., Bopp, L., Ciais, P., Chini, L., Ciais, P., Doney, S., Gkritzalis, T., Goll, D., Harris, I., Haverd, V., Hoffman, F., Hoppema, M., Houghton, R., Hurtt, G., Ilyina, T., Jain, A., Johannessen, T., Jones, C., Kato, E., Keeling, R., Klein Goldewijk, K., Landschützer, P., Lefèvre, N., Lienert, S., Liu, Z., Lombardozzi, D., Metzl, N., Munro, D., Nabel, J., Nakaoka, S. I., Neill, C., Olsen, A., Ono, T., Patra, P., Peregon, A., Peters, W., Peylin, P., Pfeil, B., Pierrot, D., Poulter, B., Rehder, G., Resplandy, L., Robertson, E., Rocher, M., Rödenbeck, C., Schuster, U., Skjelvan, I., Séférian, R., Skjelvan, I., Steinhoff, T., Sutton, A., Tans, P., Tian, H., Tilbrook, B., Tubiello, F., Van Der Laan-Luijkx, I., Van Der Werf, G., Viovy, N., Walker, A., Wiltshire, A., Wright, R., Zaehle, S. and Zheng, B.: Global Carbon Budget 2018, Earth Syst. Sci. Data, 10(4), 2141–2194, https://doi.org/10.5194/essd-10-2141-2018, 2018.

Reichstein, M., Ciais, P., Papale, D., Valentini, R., Running, S., Viovy, N., Cramer, W., Granier, A., Ogée, J., Allard, V., Aubinet, M., Bernhofer, C., Buchmann, N., Carrara, A., Grünwald, T., Heimann, M., Heinesch, B., Knohl, A., Kutsch, W., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J. M., Pilegaard, K., Pumpanen, J., Rambal, S., Schaphoff, S., Seufert, G., Soussana, J. F., Sanz,

M. J., Vesala, T. and Zhao, M.: Reduction of ecosystem productivity and respiration during the European summer 2003 climate anomaly: A joint flux tower, remote sensing and modelling analysis, Glob. Chang. Biol., 13(3), 634–651, https://doi.org/10.1111/j.1365-2486.2006.01224.x, 2007.

Reichstein, M., Bahn, M., Ciais, P., Frank, D., Mahecha, M. D., Seneviratne, S. I., Zscheischler, J., Beer, C., Buchmann, N., Frank, D. C., Papale, D., Rammig, A., Smith, P., Thonicke, K., Van Der Velde, M., Vicca, S., Walz, A. and Wattenbach, M.: Climate extremes and the carbon cycle, Nature, 500(7462), 287–295, https://doi.org/10.1038/nature12350, 2013.

Saleska, S. R., Didan, K., Huete, A. R. and Da Rocha, H. R.: Amazon forests green-up during 2005 drought, Science, 318(5850), 612, doi:10.1126/science.1146663, 2007.

Sankaran, M., Hanan, N. P., Scholes, R. J., Ratnam, J., Augustine, D. J., Cade, B. S., Gignoux, J., Higgins, S. I., Le Roux, X., Ludwig, F., Ardo, J., Banyikwa, F., Bronn, A., Bucini, G., Caylor, K. K., Coughenour, M. B., Diouf, A., Ekaya, W., Feral, C. J., February, E. C., Frost, P. G. H., Hiernaux, P., Hrabar, H., Metzger, K. L., Prins, H. H. T., Ringrose, S., Sea, W., Tews, J., Worden, J. and Zambatis, N.: Determinants of woody cover in African savannas, Nature, 438(7069), 846–849, https://doi.org/10.1038/nature04070, 2005.

Scott, R. L., Jenerette, G. D., Potts, D. L. and Huxman, T. E.: Effects of seasonal drought on net carbon dioxide exchange from a woody-plant-encroached semiarid grassland, J. Geophys. Res. Biogeosciences, 114(4), 1–13, https://doi.org/10.1029/2008JG000900, 2009.

Sippel, S., Reichstein, M., Ma, X., Mahecha, M. D., Lange, H., Flach, M. and Frank, D.: Drought, Heat, and the Carbon Cycle: a Review, Curr. Clim. Chang. Reports, 4(3), 266–286, https://doi.org/10.1007/s40641-018-0103-4, 2018.

Song, L., Luis, G., Guan, K., You, L., Huete, A., Ju, W. and Zhang, Y.: Satellite sun-induced chlorophyll fluorescence detects early response of winter wheat to heat stress in the Indian Indo-Gangetic Plains, Glob. Chang. Biol., 24, 4023–4037, https://doi.org/10.1111/gcb.14302, 2018.

Stocker, B. D., Zscheischler, J., Keenan, T. F., Prentice, I. C., Peñuelas, J. and Seneviratne, S. I.: Quantifying soil moisture impacts on light use efficiency across biomes, New Phytol., 218(4), 1430–1449, https://doi.org/10.1111/nph.15123, 2018.

Stocker, B. D., Zscheischler, J., Keenan, T. F., Prentice, I. C., Seneviratne, S. I. and Peñuelas, J.: Drought impacts on terrestrial primary production underestimated by satellite monitoring, Nat. Geosci., 12, 274-270, https://doi.org/10.1038/s41561-019-0318-6, 2019.

Thum, T., Aalto, T., Laurila, T., Aurela, M., Kolari, P. and Hari, P.: Parametrization of two photosynthesis models at the canopy scale in a northern boreal Scots pine forest, Tellus, Ser. B Chem. Phys. Meteorol., 59(5), 874–890, https://doi.org/10.1111/j.1600-0889.2007.00305.x, 2007.

Van Dijk, A. I. J. M. and Dolman, A. J.: Estimates of CO_2 uptake and release among European forests based on eddy covariance data, Glob. Chang. Biol., 10(9),

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

1445–1459, https://doi.org/10.1111/j.1365-2486.2004.00831.x, 2004.

Vicente-Serrano, S. M., Gouveia, C., Camarero, J. J., Beguería, S., Trigo, R., López-Moreno, J. I., Azorín-Molina, C., Pasho, E., Lorenzo-Lacruz, J., Revuelto, J., Morán-Tejeda, E. and Sanchez-Lorenzo, A.: Response of vegetation to drought time-scales across global land biomes, Proc. Natl. Acad. Sci. U. S. A., 110(1), 52–57, https://doi.org/10.1073/pnas.1207068110, 2013.

Wang, L. and Yuan, X.: Two Types of Flash Drought and Their Connections with Seasonal Drought, Adv. Atmos. Sci., 35(12), 1478–1490, https://doi.org/10.1007/s00376-018-8047-0, 2018.

Wang, L., Yuan, X., Xie, Z., Wu, P. and Li, Y.: Increasing flash droughts over China during the recent global warming hiatus, Sci. Rep., 6, 30571, https://doi.org/10.1038/srep30571, 2016.

Williams, C. A. and Albertson, J. D.: Soil moisture controls on canopy-scale water and carbon fluxes in an African savanna, Water Resour. Res., 40(9), 1–14, https://doi.org/10.1029/2004WR003208, 2004.

Wilson, K. B., Baldocchi, D. D. and Hanson, P. J.: Quantifying stomatal and non-stomatal limitations to carbon assimilation resulting from leaf aging and drought in mature deciduous tree species, Tree Physiol., 20, 787–797, https://doi.org/10.1093/treephys/20.12.787, 2000.

Wolf, S., Eugster, W., Ammann, C., Häni, M., Zielis, S., Hiller, R., Stieger, J., Imer, D., Merbold, L. and Buchmann, N.: Erratum: Contrasting response of grassland versus forest carbon and water fluxes to spring drought in Switzerland

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

Hydrology and Earth System Sciences Discussions

(Environmental Research Letters (2013) 8 (035007)), Environ. Res. Lett., 9(8), https://doi.org/10.1088/1748-9326/9/8/089501, 2014.

Wolf, S., Keenan, T. F., Fisher, J. B., Baldocchi, D. D., Desai, A. R., Richardson, A. D., Scott, R. L., Law, B. E., Litvak, M. E. and Brunsell, N. A.: Warm spring reduced carbon cycle impact of the 2012 US summer drought, 113(21), 5880-5885, https://doi.org/10.1073/pnas.1519620113, 2016.

Xie, Z., Wang, L., Jia, B. and Yuan, X.: Measuring and modeling the impact of a severe drought on terrestrial ecosystem CO_2 and water fluxes in a subtropical forest, J. Geophys. Res. Biogeosciences, 121(10), 2576–2587, https://doi.org/10.1002/2016JG003437, 2016.

Xu, C., McDowell, N. G., Fisher, R. A., Wei, L., Sevanto, S., Christoffersen, B. O., Weng, E. and Middleton, R. S.: Increasing impacts of extreme droughts on vegetation productivity under climate change, Nat. Clim. Chang., https://doi.org/10.1038/s41558-019-0630-6, 2019.

Yuan, W., Cai, W., Chen, Y., Liu, S., Dong, W., Zhang, H., Yu, G., Chen, Z., He, H., Guo, W., Liu, D., Liu, S., Xiang, W., Xie, Z., Zhao, Z. and Zhou, G.: Severe summer heatwave and drought strongly reduced carbon uptake in Southern China, Sci. Rep., 6, 18813, https://doi.org/10.1038/srep18813, 2016.

Yuan, W., Zheng, Y., Piao, S., Ciais, P., Lombardozzi, D., Wang, Y., Ryu, Y., Chen, G., Dong, W., Hu, Z., Jain, A. K., Jiang, C., Kato, E., Li, S., Lienert, S., Liu, S., Nabel, J. E. M. S., Qin, Z., Quine, T., Sitch, S., Smith, W. K., Wang, F., Wu, C., Xiao, Z. and Yang, S.: Increased atmospheric vapor pressure deficit reduces global vegetation growth, Sci. Adv., 5(8), eaax1396, https://doi.org/10.1126/sciadv.aax1396, 2019a.

Yuan, X., Ma, Z., Pan, M. and Shi, C.: Microwave remote sensing of flash droughts during crop growing seasons, 17, 8196, https://doi.org/10.1002/2015GL064125, 2015.

Yuan, X., Wang, L. and Wood, E. F.: Anthropogenic intensification of southern African flash droughts as exemplified by the 2015/16 season, Bull. Am. Meteorol. Soc., https://doi.org/10.1175/BAMS-D-17-007.1, 2017.

Yuan, X., Wang, L., Wu, P., Ji, P., Sheffield, J. and Zhang, M.: Anthropogenic shift towards higher risk of flash drought over China, Nat. Commun., 10(1), https://doi.org/10.1038/s41467-019-12692-7, 2019b.

Zeng, Z., Piao, S., Li, L. Z. X., Wang, T., Ciais, P., Lian, X., Yang, Y., Mao, J., Shi, X. and Myneni, R. B.: Impact of Earth greening on the terrestrial water cycle, J. Clim., 31(7), 2633–2650, https://doi.org/10.1175/JCLI-D-17-0236.1, 2018.

Zhou, S., Yu, B., Huang, Y. and Wang, G.: The effect of vapor pressure deficit on water use efficiency at the subdaily time scale, Geophys. Res. Lett., 41(14), 5005–5013, https://doi.org/10.1002/2014GL060741, 2014.

Zhou, S., Bofu, Y., Huang, Y. and Wang, G.: Daily underlying water use efficiency for AmeriFlux sites, J. Geophys. Res. Biogeosciences, 120, 887–902, https://doi.org/10.1002/2015JG002947, 2015.

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

Hydrology and Earth System Sciences
Discussions
Open Access

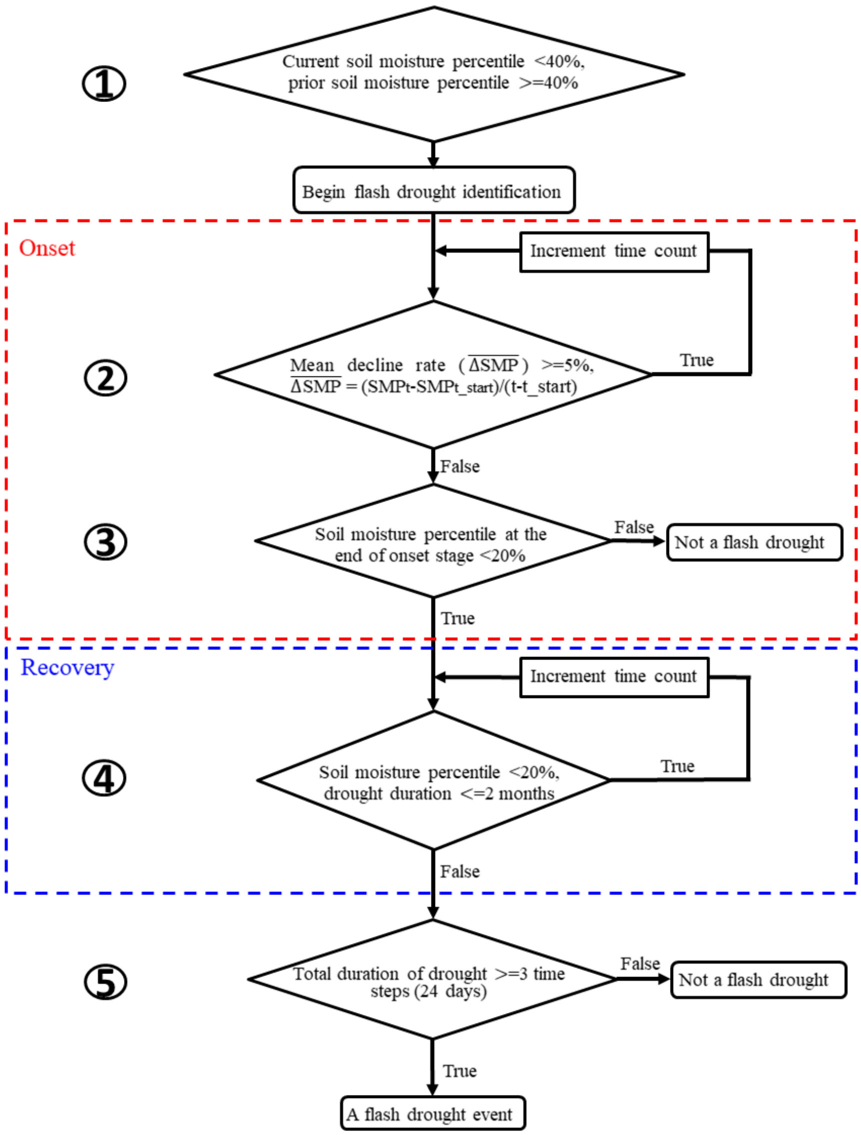


Figure 1. A flowchart of flash drought identification by considering soil moisture decline rate and drought persistency.

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

Hydrology and Earth System Sciences
Discussions

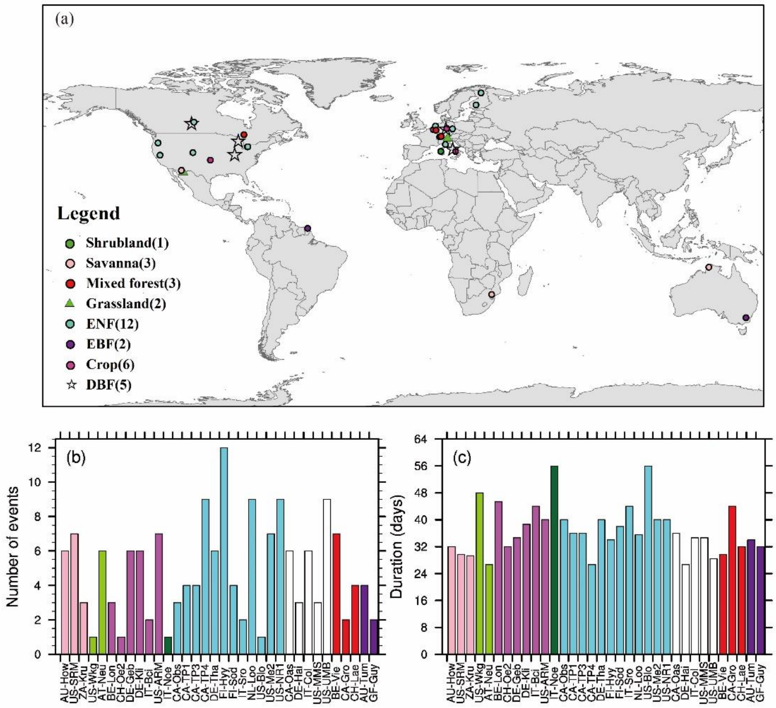


Figure 2. Flash drought characteristics. (a) Global map of 34 FLUXNET sites used in this study. (b) Total numbers (events) and (c) mean durations (days) of flash drought events for each site during their corresponding periods (see Table 1 for details). Different colors represent different vegetation types.

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

Hydrology and Earth System Sciences
Open Access
EGU
Discussions

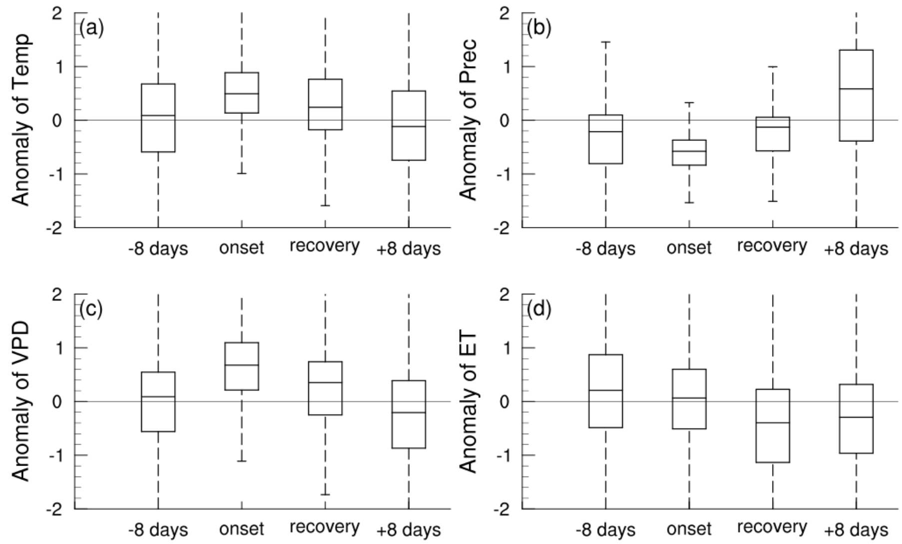


Figure 3. Standardized 8-day anomalies of (a) temperature, (b) precipitation, (c) VPD, and (d) ET during 8 days prior to flash drought onset, onset and recovery stages of flash drought, and 8 days after flash drought.

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

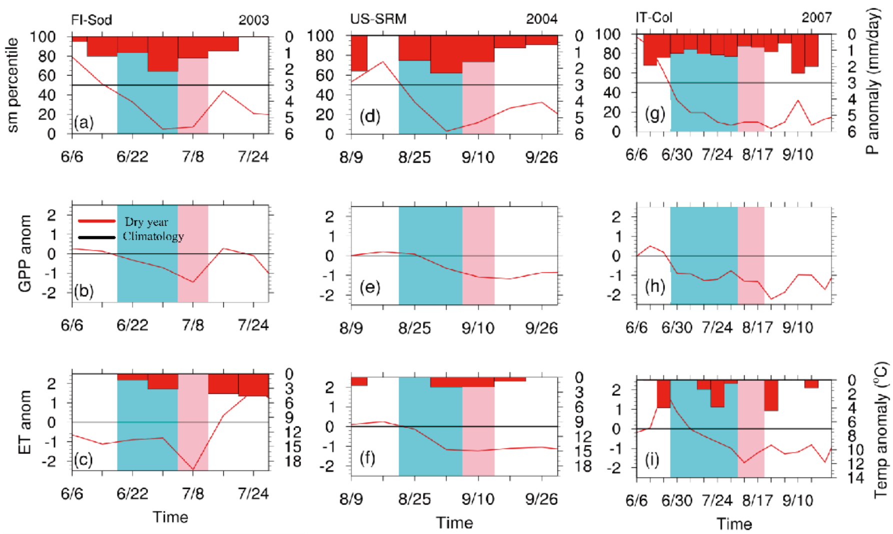
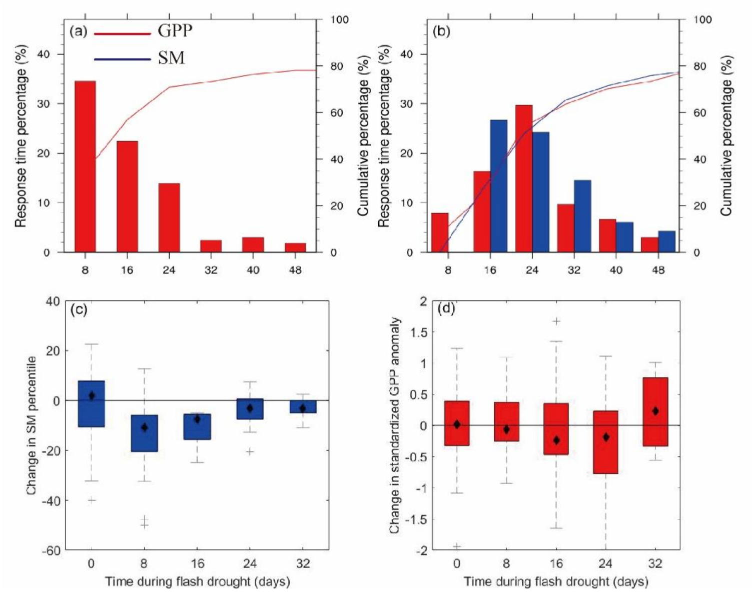


Figure 4. Time series of soil moisture percentile (top panels), standardized gross primary productivity (GPP) anomaly (middle panels) and standardized evapotranspiration (ET) anomaly (bottom panels) for the 2003 drought at FI-Sod station, 2004 drought at US-SRM station and 2007 drought at IT-Col station. Red lines are the time series in the target year, and black lines are the climatology (long-term mean values). The red bars are precipitation deficits in top panels and temperature anomalies in bottom panels, where data with positive precipitation anomaly or negative temperature anomaly are not shown. The blue and pink shaded areas are the onset and recovery stages of flash drought events, respectively.

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

Hydrology and Earth System Sciences
Open Access
Discussions

678 

679 **Figure 5.** Response of carbon fluxes to flash droughts. (a) Percentage of the response
680 time of the first occurrence of negative GPP anomaly and (b) the minimum values of
681 GPP (red bars) and soil moisture (blue bars) during flash droughts. The temporal
682 change rates of (c) soil moisture percentiles and (d) standardized GPP anomalies
683 before and during flash droughts.

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

Hydrology and Earth System Sciences Discussions

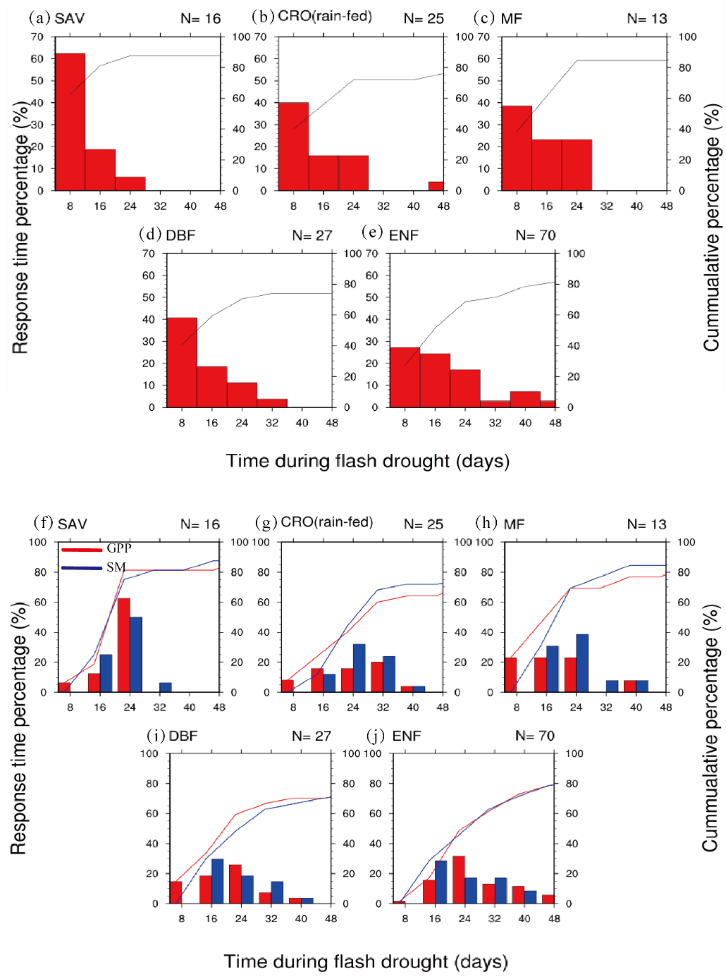


Figure 6. Percentage of the response time (days) of the first occurrence of negative GPP anomaly, minimum GPP anomaly and minimum soil moisture percentile during flash drought for different vegetation types. SAV: savanna, CRO: rainfed cropland, MF: mixed forest, DBF: deciduous broadleaf forest and ENF: evergreen needleleaf forest.

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

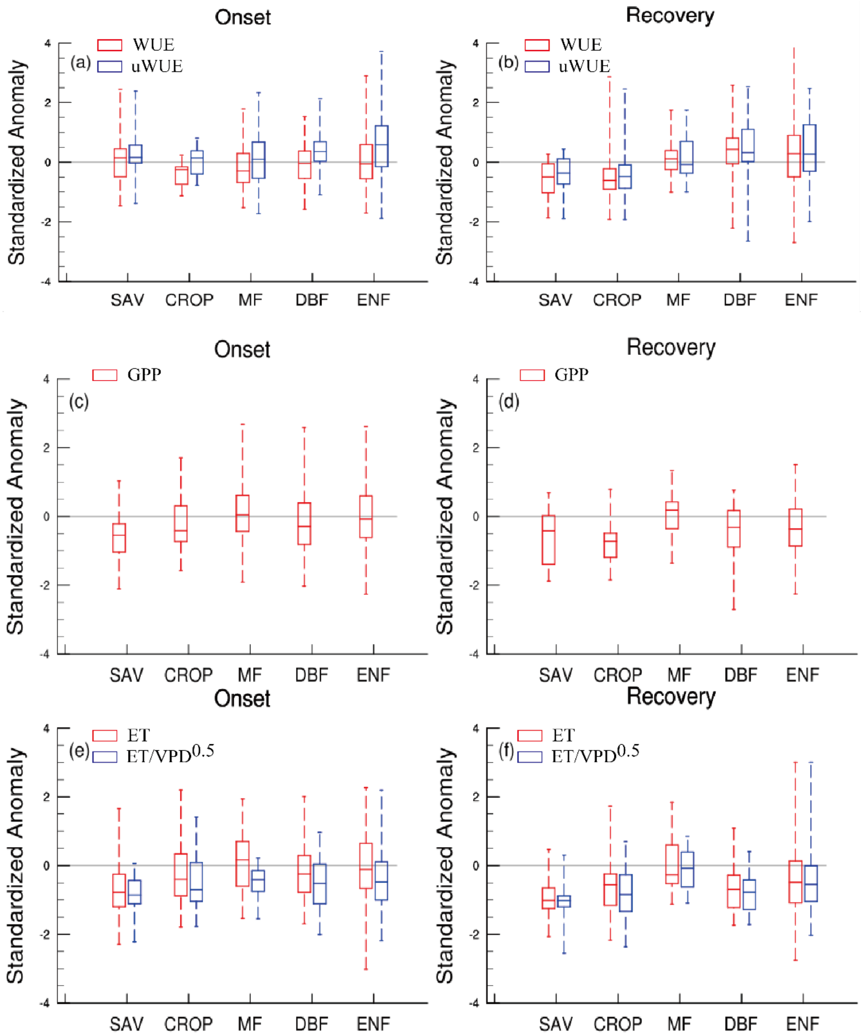


Figure 7. Standardized anomalies of water use efficiency (WUE), underlying WUE (uWUE), GPP, ET and $ET/\sqrt{VPD}$ during onset and recovery stages of flash drought events. SAV: savanna; CROP: cropland; MF: mixed forest; DBF: deciduous broadleaf forest; ENF: evergreen needleleaf forest.

https://doi.org/10.5194/hess-2020-185
Preprint. Discussion started: 8 May 2020

Hydrology and Earth System Sciences
Discussions

Table 1. Locations, vegetation types and data periods of Flux Tower Sites used in this study. WSA: woody savanna; CROP: cropland; EBF: evergreen broadleaf forests; MF: mixed forest; DBF: deciduous broadleaf forest; ENF: evergreen needleleaf forest; GRA: grassland; SAV: savanna.

station	lat	lon	IGBP	period
AT-Neu	41.12	11.32	GRA	2002-2012
AU-How	-12.49	131.15	WSA	2002-2014
AU-Tum	-35.66	148.15	EBF	2002-2014
BE-Lon	50.55	4.75	CROP-rainfed	2004-2014
BE-Vie	50.31	6.00	MF	1997-2014
CA-Gro	48.22	-82.16	MF	2004-2013
CA-Oas	53.63	-106.20	DBF	1996-2010
CA-Obs	53.99	-105.12	ENF	1999-2010
CA-TP1	42.66	-80.56	ENF	2002-2014
CA-TP3	42.71	-80.35	ENF	2002-2014
CA-TP4	42.71	-80.36	ENF	2002-2014
CH-Lae	47.48	8.37	MF	2005-2014
CH-Oe2	47.29	7.73	CROP-rainfed	2004-2014
DE-Geb	51.10	10.91	CROP-rainfed	2001-2014
DE-Hai	51.08	10.45	DBF	2000-2012
DE-Kli	50.89	13.52	CROP-rainfed	2005-2014
DE-Tha	50.96	13.57	ENF	1997-2014
FI-Hyy	61.85	24.29	ENF	1997-2014
FI-Sod	67.36	26.64	ENF	2001-2014
GF-Guy	5.28	-52.92	EBF	2004-2014
IT-Bci	40.52	14.96	CROP-irrigated	2005-2014
IT-Col	41.85	13.59	DBF	2005-2014
IT-Noe	40.61	8.15	SH	2004-2014
IT-Sro	43.73	10.28	ENF	2000-2012
NL-Loo	52.17	5.74	ENF	1999-2013
US-ARM	36.61	-97.49	CROP-rainfed	2003-2013
US-Blo	38.90	-120.63	ENF	1998-2007
US-Me2	44.45	-121.56	ENF	2002-2014
US-MMS	39.32	-86.41	DBF	1999-2014
US-NR1	40.03	-105.55	ENF	2002-2014
US-SRM	31.82	-110.87	WSA	2004-2014
US-UMB	45.56	-84.71	DBF	2002-2014
US-Wkg	31.74	-109.94	GRA	2005-2014
ZA-Kru	-25.02	31.50	SAV	2000-2010