Response to the comments from Reviewer #1

We are grateful to the reviewer for the constructive and careful review. We have incorporated the comments to the extent possible. The reviewer's comments are italicized and our responses immediately follow.

General Comments:

1) Terminology-Because the definition for flash drought recovery focuses on changes in soil moisture, this framework introduces some confusion when also used to examine changes in GPP given the lag between the onset of soil moisture drought and its impact on vegetation health. For example, it is counterintuitive to refer to periods of "recovery" as those that also have substantial reductions in GPP. I think the framework used in this study is okay, but that different terminology needs to be used when referring to these periods because the "recovery" is only with respect to soil moisture conditions. The new terminology will need to be used in the abstract, and throughout the paper. It would also help to remind the reader at various stages of the paper that "flash drought" refers to "soil moisture flash drought"

Response: Thanks for your comments. We have revised "flash drought" as "soil moisture flash drought" throughout the paper.

2) Definition-I think it's fine that you chose to add a maximum length threshold (lines128-131) to the flash drought definition if you also want to solely focus on sub-seasonal drought events. However, this choice, and its impact on the resultant analysis, needs to be clearly noted in the revised text. For example, limiting flash drought duration to no more than two months means that situations where a period of rapid intensification preceded development of a longer-term drought will be excluded from the climatology because the soil moisture will not rise to greater than the 20th percentile within the chosen period of time. In fact, many of the most notable flash drought events discussed in the introduction (such as the 2012 U.S. flash drought) would presumably not be classified as flash drought with this methodology because the period of rapid intensification itself lasted for two or more months after that. In *reality, the method used in this study only examines a subset of flash droughts, where not only must they exhibit a period of rapid intensification over 1-2 months, but then the drought conditions themselves must also be completely eliminated within another month. So, there are sub-seasonal events in their entirety. This is alluded to at lines 193-195. To reiterate, I think the methodology itself is okay, but that is needs to be clearly stated at various points of the text (abstract, methods, results, discussion, conclusions) that the goal is to look "only" at flash drought events that develop and decay over a single season, and that the method will exclude flash droughts that subsequently develop into long-term drought.*

Response: Thanks for your comments. Here we concern the rapid intensification and the recovery of soil moisture for identifying flash droughts, but soil moisture percentiles does not necessarily recover to above 20% within two months. The maximum duration of 2 months is used to focus on the sub-seasonal droughts, rather than the long-term droughts. Therefore, 2012 U.S. flash drought could be identified according to the methodology used in this study. And we have clarified in the manuscript as follows:

"For example, if the soil moisture percentile does not recover to above 20% within 2 months and develops into a long-term drought (with duration longer than 2 months), only the first 2 months are used for the analysis since we focus on the sub-seasonal time scale in this study." (L155-158)

3) Section 3.3-This section needs to be substantially revised. Given that the focus elsewhere in the paper has been to evaluate the results based on the vegetation type, it is confusing why this section primarily focuses on analyzing the results accumulated over all vegetation types in Fig.5., before then very briefly discussing vegetation specific results in Fig.6. It would be much more insightful, and consistent with the rest of the paper, if you were to instead expand the existing briefly analysis for each of the vegetation types into something more substantial. This would result in the removal of Fig.5 that focuses on all of the stations in aggregate and redoing the bottom panels in Fig.5 so that they can be added to Fig.6 for each individual vegetation type. This will *then allow you to continue to examine the time series for each vegetation type as has been done elsewhere in the paper.*

Response: Thanks for your constructive comments. We have revised the manuscript as follows:

"Figure 5 shows the probability distributions of the response time of GPP to soil moisture flash drought as determined by soil moisture reductions for the first occurrence of negative SGPPA, the minimum negative value of SGPPA and the minimum soil moisture percentiles for different vegetation types, respectively. To reduce the uncertainty due to small sample sizes, only the results for vegetation types (SAV, CROP, MF, DBF, ENF) with more than 10 flash drought events are shown. For soil moisture flash droughts from all vegetation types, the first occurrences of negative SGPPA are concentrated during the first 24 days, and GPP starts to respond to soil moisture flash drought within 16 days for 57% flash droughts (Figures 5a-e). The occurrences of minimum value of SGPPA rise sharply at the beginning of soil moisture flash drought, and reach the peak during 17-24 days, and then slow down (Figures 5f-j), which is similar to the decline in soil moisture. Although the first occurrences of negative SGPPA mainly occur in the onset stage, GPP would continue to decrease in the recovery stages for 60% of soil moisture flash drought events. Different types of vegetation including herbaceous plants and woody plants all react to soil moisture flash drought in the early stage (Figures 5a-e). Among them, SAV shows the fastest reaction to water stress (Figures 5a and 5f), and the RT is within 8 days for 63% events, suggesting that vegetation responds concurrently with soil moisture flash drought onset. Ultimately, 88% events showing reduced vegetation photosynthesis. The result is consistent with previous studies regarding the strong response of semi-arid ecosystems to water availability (Gerken et al., 2019; Vicente-Serrano et al., 2013; Zeng et al., 2018), and the decline in GPP for SAV is related to isohydric behaviors during soil moisture drought and higher VPD, through closing stomata to decrease water loss as transpiration and carbon assimilation (Novick et al., 2016; Roman et al., 2015). For ENF, the first negative SGPPA occurs within the first 8 days for 27% of the soil moisture flash droughts. When the RT is within 40 days, the cumulative frequency ranges from 74% to 88% among different vegetation types. The response frequency of RTmin and the response time of minimum soil moisture percentiles are quite similar, although there are discrepancies among the patterns of the response frequency for different vegetation types. The response frequency of RTmin for SAV increases sharply during 17-24 days of soil moisture flash droughts (Figure 5f). GPP is derived from direct eddy covariance observations of NEP and terrestrial ecosystem respiration and the response of NEP to flash droughts show the compound effects of vegetation photosynthesis and ecosystem respiration. In terms of RT, the response of NEP is slower than GPP for SAV, but is quicker for DBF and ENF (Figure S1). The discrepancies between NEP and SM in terms of RTmin are more obvious than those between GPP and SM, and the RTmin of NEP is much quicker than the RTmin of soil moisture especially for DBF and ENF, which may relate to the increase of ecosystem respiration (Figure S1 i and j).

Figure 6 shows that the temporal changes of SGPPA and soil percentiles during 8 days before flash droughts and the first 24 days of soil moisture flash droughts. During 8 days before flash droughts, there is nearly no obvious decline for SGPPA, and SAV and ENF show small increase in GPP. The decline in SGPPA is more significant during the first 9-24 days of soil moisture flash droughts for different vegetation types and SGPPA for SAV shows quicker decline even during the first 8 days of soil moisture flash droughts. The rapid decline rates in soil moisture are mainly concentrated within the first 16 days of flash droughts and show differences among different vegetation types during soil moisture flash drought, which are related to soil texture, vegetation cover and climates. There are various lag times between the response of GPP to the decline in soil moisture among different vegetations.” (L319-377)

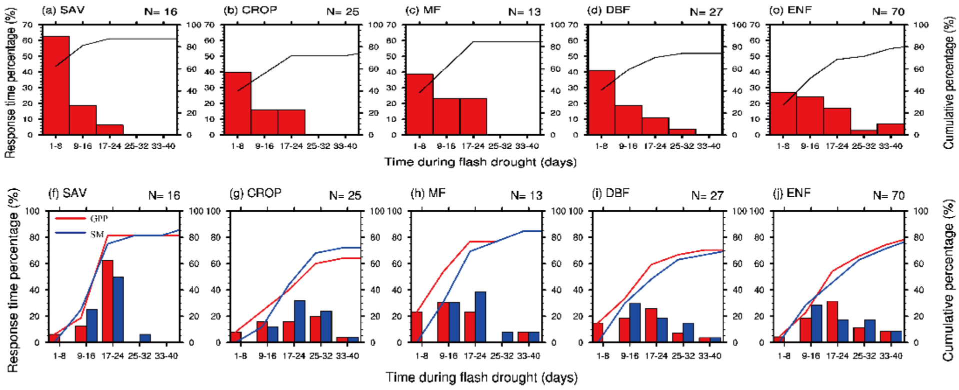

Figure 5. Percentage of the response time (days) of the first occurrence of negative GPP anomaly (a-e), minimum GPP anomaly and minimum soil moisture percentile (f-j) during flash drought for different vegetation types. SAV: savanna, CROP: rainfed cropland, MF: mixed forest, DBF: deciduous broadleaf forest and ENF: evergreen needleleaf forest.

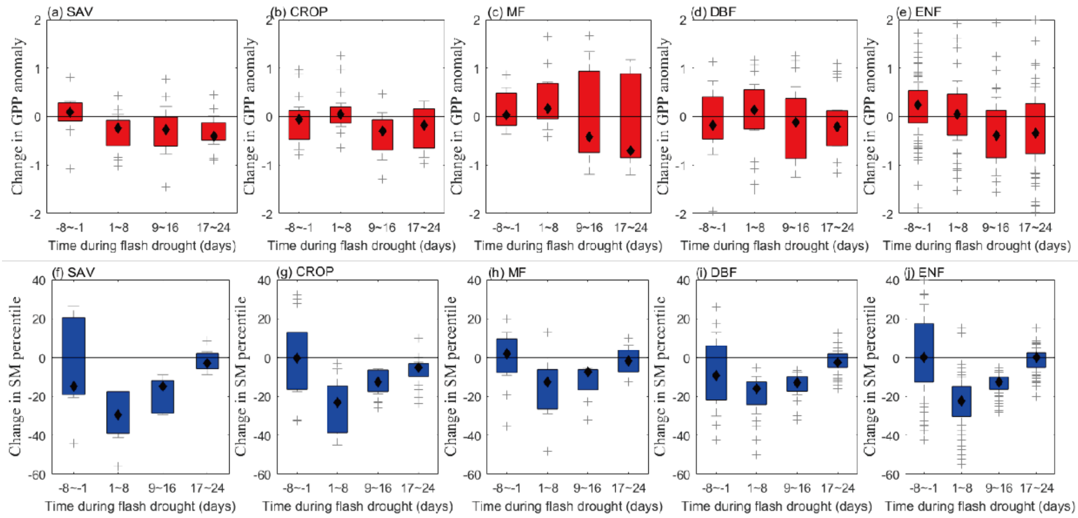

Figure 6. The temporal change rates of standardized GPP anomalies (a-e) and soil moisture percentiles (f-j) for different vegetation types. SAV: savanna, CROP: rainfed cropland, MF: mixed forest, DBF: deciduous broadleaf forest and ENF: evergreen needleleaf forest.

Specific Comments:

4) Line 37-Insert "future" before "land carbon uptake" in this sentence.

5) Line 58-Please add the Svoboda et al. (2002) reference for the U.S. Drought Monitor.

Response: Revised as suggested.

6) Line 59-This drought also impacted parts of southern Canada.

Response: Thanks for your comments. He et al. (2019) assessed the impacts on vegetation productivity of the flash drought across the U.S. Northern Great Plains, excluding Canadian Prairies.

7) Line 78-Few studies, or no studies have investigated this parameter? If there are previous studies, please cite them here.

8) Introduction-It would also be good to cite the Otkin et al. (2018; WCAS) paper because they examined the impact of a flash drought on vegetation health across the north-central U.S.

Response: Revised as suggested.

9) Line 99-Please add some additional information about the soil moisture sensors, such as their type, their accuracy, and how they are sited. It would also be good to know what the soil type is for each of the stations.

Response: Thanks for your comments. We have revised the manuscript as follows: "Considering most sites only measure the surface soil moisture, here we use daily soil moisture measurements mainly at the depth of 5-10 cm averaged from half-hourly data. Soil moisture observations are usually averaged over multiple sensors including time domain reflectometer (TDR), frequency domain reflectometer (FDR), and water content reflectometer etc. However, the older devices may be replaced with newer devices at certain sites, which may decrease the stability of long-term soil moisture observations and the average observation error of soil moisture is ±2%." (L123-130)

10) Line 103-106 -How were these vegetation classifications determined? I think it would also be good to briefly discuss the phenological characteristics of these classifications.

Response: Thanks for your comments. We have revised the manuscript as follows:

“The vegetation classification is according to International Geosphere-Biosphere Program (IGBP; Belward et al., 1999), where MF is dominated by neither deciduous nor evergreen tree types with tree cover larger than 60%, and the land tree cover is 10-30% for SAV.” (L116-119)

11) Line 106- Please make this sentence explicit rather than simply stating “etc”. Also, this would be a good spot to point the readers to the top panel in Fig.2 to see the locations of these stations.

Response: Thanks for your comments. We have revised the manuscript as follows:

“The FLUXNET observations include 12 evergreen needleleaf forest sites (ENF), 5 deciduous broadleaf forests (DBF), 6 crop sites (CROP; 5 rain-fed sites and 1 irrigated site), 3 mixed forests (MF), 3 savannas (SAV), 2 grasslands (GRASS), 2 evergreen broadleaf forests (EBF) and 1 shrubland (Shrub).” (L112-116)

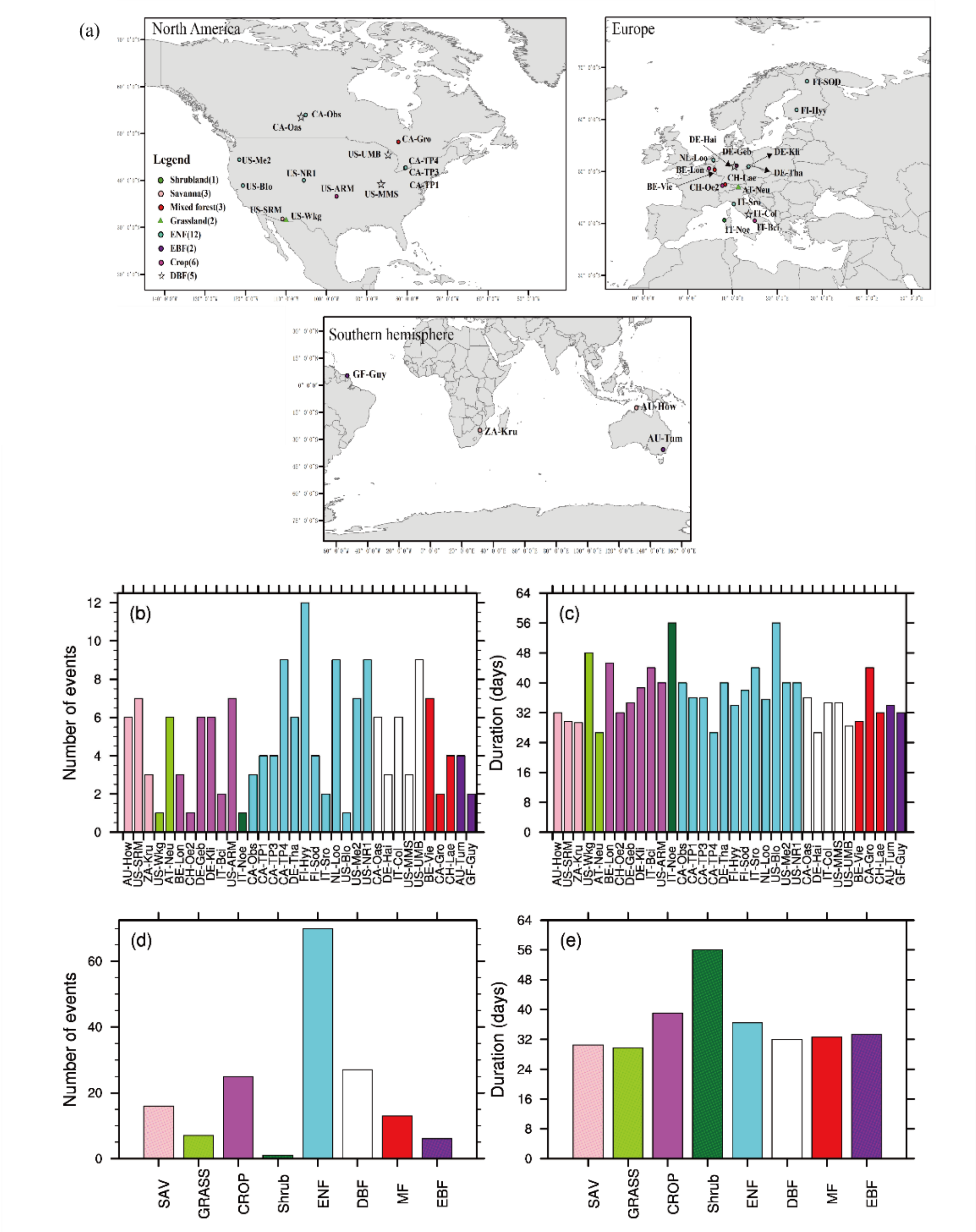

Figure 2. Flash drought characteristics. (a) Global map of 34 FLUXNET sites used in this study. (b&d) Total numbers (events) and (c&e) mean durations (days) of flash drought events for each site and vegetation type during their corresponding periods (see Table 1 for details). Different colors represent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

12) Lines 106-108-Please provide some justification for why these three particular sites were chosen for the case study analyses. It would also be helpful to mention here where these three stations are located, and a brief overview of their climate *characteristics. For example, are there stations located in regions that are known to frequently experience flash droughts?*

Response: Thanks for your comments. Here the selected three sites represent different ecosystems including savanna, evergreen needleleaf forest, and deciduous broadleaf forest, which are located at high latitude and middle latitude with distinguished climates, respectively. We have revised the manuscript as follows:

"Here we select FI-Sod site (26.64°E, 67.36°N), US-SRM site (110.87°W, 31.82°N) and IT-Col site (13.59°E, 41.85°N) to show the response of vegetation to flash droughts for different ecosystems and different climate. FI-Sod is with the mean annual precipitation of 500 mm yr^{-1} and the mean annual temperature of -1℃, and it is green all the year dominated by woody vegetation of ENF. The mean annual temperature and precipitation for US-SRM are 18℃ and 380 mm yr^{-1}, respectively. US-SRM is located at SAV covered by herbaceous and other understory systems. IT-Col is dominated by DBF with leaf-on and leaf-off periods and the mean annual temperature and precipitation are 6.3℃ and 1180 mm yr^{-1}." (L120-129)

13) Line 116-Does the first day of the flash drought occur at the beginning, middle, or end of the 8-day period used to compute the mean conditions? Please clarify.

Response: Thanks for your comments. We have revised the manuscript as follows:

"1) Soil moisture flash drought starts at the middle day of the 8-day period when the 8-day mean soil moisture is less than the 40^{th} percentile, and the 8-day mean soil moisture prior to the starting time should be higher than 40^{th} percentile to ensure the transition from a non-drought condition." (L138-142)

14) Figure 1-The label between steps 2 and 3 should be "true". The box for step five should also be expanded to include "and <2 months". Please correct these errors.

Response: Thanks for your comments. We have revised the manuscript as follows:

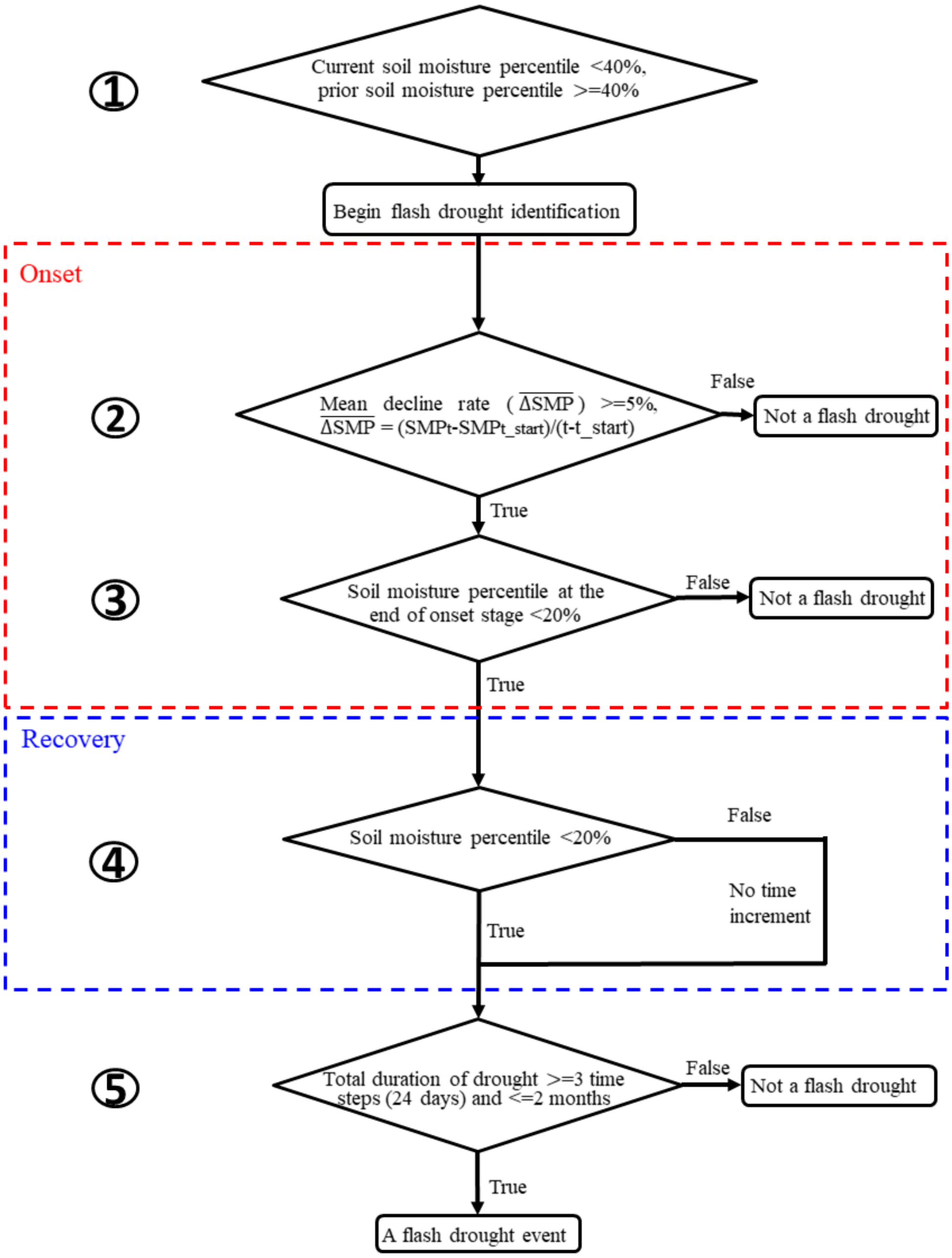

Figure 1. A flowchart of flash drought identification by considering soil moisture decline rate and drought persistency.

15) Line 119-It would be good to note here that these differences are also being computed at 8-day increments to match the cadence of the 8-day mean periods.

Response: Thanks for your comments. We have revised the manuscript as follows:

"2) The mean decreasing rate of 8-day mean soil moisture percentile should be no less than 5% per 8 days to address the rapid drought intensification." (L142-143)

16) Lines 123-125-"Recovery" is imprecise here because a decrease of 4% from one period to the next does not represent recovery; instead, it simply means that the deterioration is not fast enough to meet the threshold for a flash drought used in this study. Please change this term to "stabilization", or something similar, because that will permit some degradation to still occur. Note that this only refers to the soil moisture status "stabilizing", thus, the inconsistency with respect to the vegetation parameters (see Major Comment#1) still remains and will also need to be properly addressed.

Response: Thanks for your comments. The end of the onset stage of flash drought occurs when the **mean decline rate** is smaller than 5% in percentiles per 8 days, which would avoid such phenomenon that the soil moisture percentiles are still declining after the onset stage as much as possible. And we compared the soil moisture percentiles during recovery stages and at the ending point of onset stages and the soil moisture still declines at the rate of 2~3% in percentiles per 8 days only for 3% of flash drought events (Figure R1). Therefore, the soil moisture percentiles during the identified recovery stages increase as compared with the ending point of onset stages for most cases.

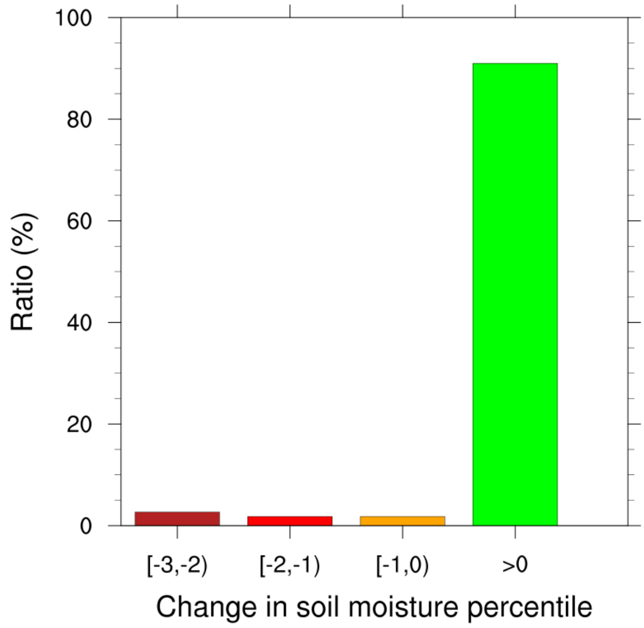

Figure R1. The frequency of soil moisture percentile changes between recovery stages and the ending point of onset stages.

17) Line 132-Please change the start of this sentence to "At least decade long"

Response: Revised as suggested.

18) Line 132-140-It would be good to reiterate here that the percentiles themselves are still only computed over an 8-day period, but that the use of the surrounding 8-day periods are used to increase the sample size. These surrounding time periods though are certainly not completely independent, so please also comment on how much this approach does or does not increase the effective sample size when computing the percentiles

Response: Thanks for your comments. Figure R2 shows the probability density function of soil moisture at different time based on the climatology solely from the target time of all observation years (a_clim) and the climatology consisting of the target time and 8 days before and after the target time of all observation years (b_clim). The b_clim is smoother than a_clim, indicating that the extended samples would decrease the uncertainty caused by certain extreme values. We have revised the manuscript as follows:

"Besides, the target 8-day soil moisture percentiles are only based on the target 8-day soil moisture in the context of the expanded samples." (L163-164)

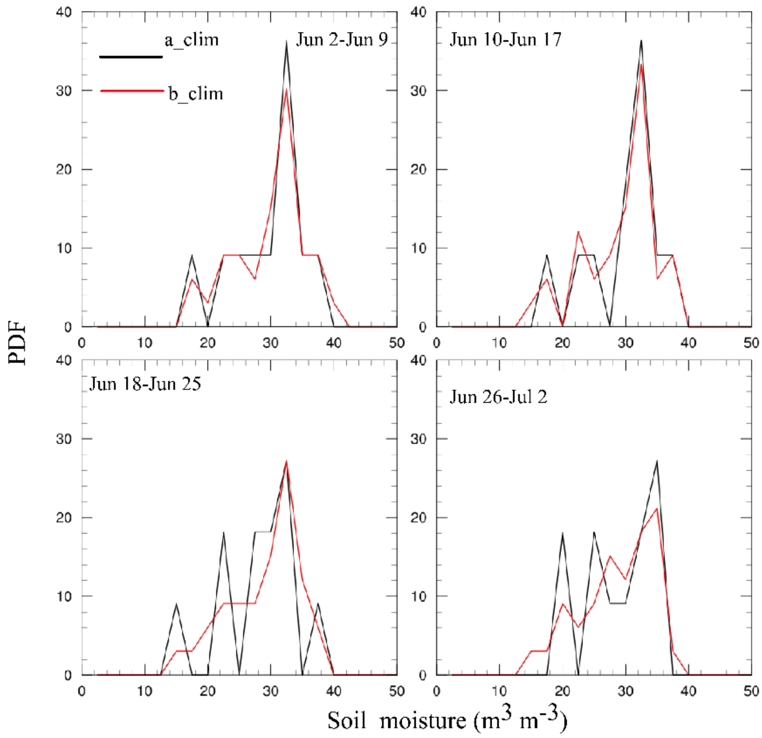

Figure R2. The probability density function of soil moisture at Jun 2-9, Jun 10-Jul 17, Jun 18-Jun 25, Jun 26-Jul 2 based on the climatology solely from the target time during all observation years (black lines; a_clim) and the climatology from not only the target time but also 8 days before and after the target time from all observation years (red lines; b_clim).

19) Lines 150-Please add the Crausbay et al. (2017) paper in BAMS that discusses ecological drought.

Response: Revised as suggested.

20) Line 154-You highlight an example with 19 years of data: however, most of the stations only have around 10 years of data. This is a short period for computing standard deviations. Please comment on how the short period of record will impact the anomalies and their subsequent use in this study.

Response: Thanks for your comments. Here the standardized deviation of GPP are also based on at least 30-sample climatology, which is same as that of soil moisture percentiles. We have revised the manuscript as follows:

"For instance, all Apr 1-8 during 1996-2014 would have a μ_{GPP} and a σ_{GPP} based on a climatology same as soil moisture percentile calculation, which consists of March 24-31, Apr 1-8, and Apr 9-16 in all years, and Apr 9-16 would have another μ_{GPP} and another σ_{GPP}" (L184-187)

21) Lines 154-157-The example provided in this sentence implies that ecological drought always happens one period after the flash drought first develops. Is that the true intention here? If not, please clarify this sentence. I would expect there to be more than a one period lag because in many situations, the vegetation roots will extend much deeper than the 10-cm topsoil layer used in this study to identify flash droughts, thereby allowing them to remain healthy despite a rapidly drying topsoil layer. This needs to be highlighted in this section – a flash drought in the top soil layer may not correspond to an ecological drought because of the depth of the roots.

Response: Thanks for your comments. We have revised the manuscript as follows:

"Considering flash drought is identified through surface soil moisture, vegetation with deeper roots may obtain water in deep soil moisture and remain healthy during flash drought." (L194-196)

22) Lines 150-162-It would be helpful if each of these indices were assigned separate names to be used in the results section.

23) Line 187-Please add "or equal to" before 24 days

Response: Revised as suggested.

24) Line 190-The station level average lengths are not helpful because many of the stations only have one or two events. It would be better to show the average length over all of the stations, or for all of the stations within a particular ecosystem type. Please do this in the revised text.

Response: Thanks for your comments. We have revised the manuscript as suggested and Figure 2 is shown in Response #11. The manuscript has been revised as follows:

"Figure 2a shows the distribution of the 34 sites with different vegetation types, which are mainly distributed over North America and Europe. The number of soil moisture flash drought ranges from 1 to 12 events among FLUXNET sites (Figure 2b). There are 12 ENF sites in this study, and the number of soil moisture flash droughts for ENF is the most among all the vegetation types. There are less than 10 flash droughts at GRASS, Shrub, EBF (Figure 2d). Mean durations of soil moisture flash droughts range from 30 days to 56 days and the duration for Shrub is quite high due to one extreme flash drought (Figure 2e)." (L234-242)

25) Lines 192-193-Is this sentence meant to imply that some stations may have multiple flash droughts because a single event is broken into two because of a rainfall event that temporally improves things? If so, please describe it as such, otherwise it is not clear what this sentence adds to the paper.

Response: Thanks for your comments. We have deleted this sentence.

26) Line 192-What is meant by "variability of soil moisture"? Please describe this more clearly. Also, this really means variability of precipitation since it is the ultimate cause of the variability in soil moisture.

Response: Thanks for your comments. We have deleted this sentence.

27) Figure 2-The panels on this figure are difficult to read. For example, the spatial heterogeneity briefly mentioned in the text is impossible to see in the top panel because most of the stations are crammed into central Europe or North America, and it is impossible to relate the results shown in the bottom panels to the map shown in the top panel. I suggest breaking this panel into separate panels for North America, Europe, and the other four stations individually, while still taking the same amount of space as the current panel. This will allow you to zoom into all of these regions and therefore more clearly show the spatial heterogeneity.

Response: Thanks for your comments and we have revised Figure 2 as suggested. Please refer to Response #11.

28) Lines 204-206-This sentence is imprecise. A decrease in ET will indeed limit the *loss of soil moisture; however, it does not represent an alleviation of drought conditions. For one thing, soil moisture will still be decreasing in the absence of rainfall, albeit at a slower rate. Secondly, decreasing ET actually means that agricultural or ecological drought conditions are worsening. Please clarify this statement to account for these considerations.*

Response: We have moved the analysis of ET into Section 3.4 in the revised manuscript.

29) Lines 210-211-Please add some information describing where these stations are located, and why these events were chosen for closer analysis.

Response: Thanks for your comments. We have added detailed information about the selected sites in the revised manuscript. Please refer to Response #12.

30) Figure 4-Please change the top and bottom rows so that precipitation and temperature anomalies can be both positive and negative, otherwise, the analysis is incomplete since only one part of the anomaly time series can be shown.

Response: We have revised Figure 4 as follows:

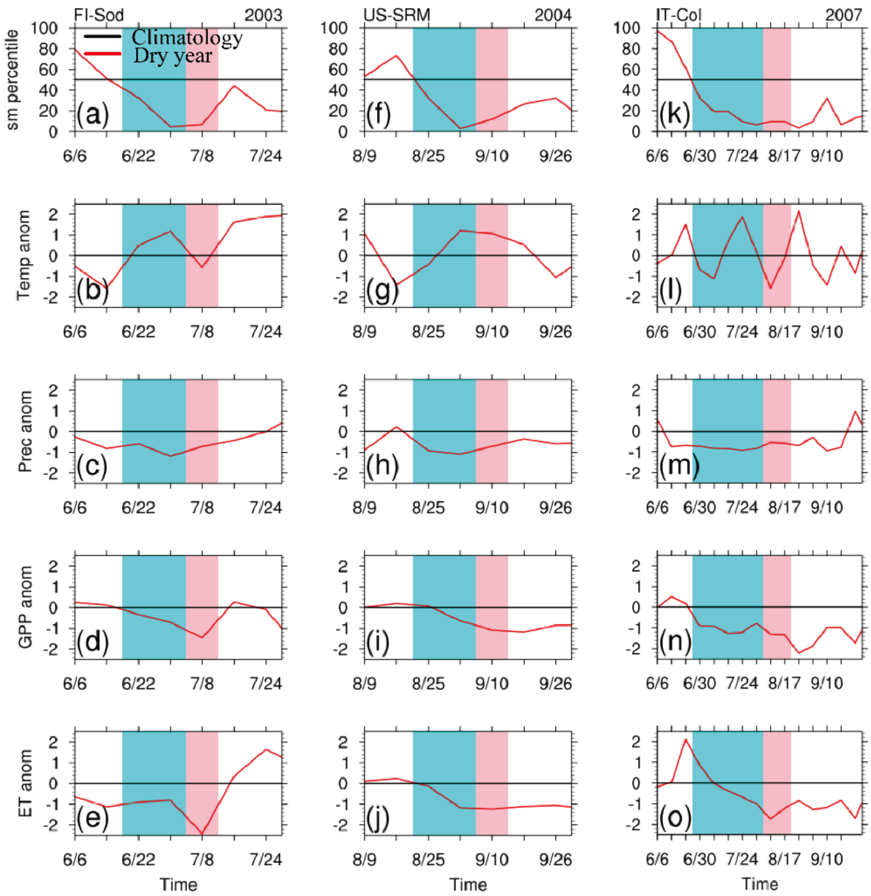

Figure 4. Time series of soil moisture percentiles (a, f, k) and standardized anomalies of temperature (b, g, l), precipitation (c, h, m), gross primary productivity (GPP; d, i, n) and evapotranspiration (ET; e, j, o) for the 2003 drought at FI-Sod station, 2004 drought at US-SRM station and 2007 drought 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 blue and pink shaded areas are the onset and recovery stages of flash drought events, respectively. (L849-858)

31) Line 220-This statement is too strong because it is based on a single case study.

Response: Thanks for your comments. We have deleted this sentence.

32) Line 228-Is there a reference that supports this statement? The variability in the time series for this station is very similar to the other two time series shown on Fig.4.

Response: Thanks for your comments. We have deleted this sentence.

33) Lines 230-231-This statement is not supported by the bottom row of Fig. 4 where the ET anomalies for this savanna station are actually less severe than those for the forested site. Please fix this in the revised text.

Response: Thanks for your comments. We have deleted this sentence.

34) Lines 212, 224, and 236-It would help if you pointed the reader toward the appropriate panels on Fig. 4 in the introductions to each of these paragraphs.

Response: Thanks for your comments. We have revised this manuscript as suggested.

35) Figure 5-Please move the legend on panel a to panel b since that is where both these lines are shown.

36) Line 252-It would be good to clarify that is "flash drought as determined by soil moisture reductions"

Response: Revised as suggested.

37) Line 279-Why "down to its normal conditions"? I assume this is a mistake since you've already shown in previous section that GPP anomalies become negative during a flash drought.

Response: Here negative GPP anomalies did not occur during all flash drought events and GPP responded to 81% of flash droughts in this study.

38) Line 284-The ratio is reversed compared to that shown at line 172.

Response: Here uWUE (GPP $\times \sqrt{VPD}/ET$) is partitioned into GPP and $ET/\sqrt{VPD}$, which is more direct when compared the response of vegetation photosynthesis and stomatal conductance to soil moisture flash droughts, respectively.

39) Line 288-Again, this terminology is confusing-how can "recovery" be accompanied by "significant reductions" in GPP and ET. Those reductions show that vegetation conditions have deteriorated, not improved. This is also repeated at lines

319-320. This terminology needs to be changed to reflect that the "recovery" is only respect to soil moisture.

40) Line 315-Please change "intensify" to "reduction".

Response: Revised as suggested.