Global observations of land-atmosphere interactions during flash drought

Response to reviewers: 2025/07/11

We would like to thank both reviewers for their helpful suggestions to improve the manuscript. All reviewer comments are addressed below and our proposed changes to the manuscript detailed. Reviewer comments are in blue italics with our responses following in black. Proposed new text for the revised manuscript is in red.

Reviewer 1

The study investigates the land-atmosphere interactions during flash droughts using daily satellite products from 2000 to 2020 for the purpose of improving the S2S predictability of flash drought. The flash drought events are identified using surface soil moisture (ESA CCI Soil moisture combined active/passive microwave product) and land-atmosphere coupling processes for composites of flash drought events are analysed using standardised anomaly of net radiation at the surface from CERES, latent heat flux from GLEAM and sensible heat flux as the difference between land surface temperature (ESA CCI) and 2m air temperature (ERA5). The study demonstrates that flash droughts with stronger land-atmosphere coupling persistent surface energy budget perturbations months before and after onset. Further, the study shows that increased sensible heat flux during flash droughts feeds back to raise near-surface air temperatures, especially in semi-arid African regions.

The manuscript is generally well-written with comprehensive details on assumptions and limitations of the data. The study provides detailed investigation of land and near-surface atmospheric variables during the flash drought; however, the current work lacks substantial conclusions with respect to knowledge gaps in S2S predictability. I think the paper could be strengthened with additional investigations on evolution of variables modulating land-atmosphere interaction for other land cover classes (shown in Figure 2) in addition to rainfed croplands.

Therefore, I recommend major revisions before publication to enhance the robustness and significance of the findings.

Thank you very much for this helpful feedback. We have created versions of Figure 3 showing the other three land cover classes from Figure 2 (shrubland, grassland and broadleaved deciduous trees) and propose to add these into the Supplementary Information, with discussion of their differences from rainfed cropland added into the main text. These figures are included at the end of this response as Figures R1, R2 and R3. The additional variables, which were plotted for rainfed cropland in Figure S3, will also be added (Figures R4, R5 and R6). These proposed changes are discussed further in response to the specific comments below. We also discuss below how we intend to strengthen our discussion of the relevance and application of our findings for S2S predictability, as we agree that this would improve the significance and reach of the paper.

Specific Comments:

Figure 2: Provide clarification on the timing of the drought event in the figure caption and discussion. The figure S2 mention the composites during peak growing season even though it is shown as accompanying figure of Figure 2.

The mention of peak growing season in the caption of Figure S2 was an error: flash droughts with onset dates in all months are included. We have verified that this error was only in the caption and all figures show the correct data. We will change the caption to remove "with onset dates during the peak growing season". To ensure complete clarity we will also add to the methods at line 107: *Flash droughts with onset dates in all months are considered.*

Figure S3: The wind speed at 10m shows substantial difference for different quartile, which suggests wind speed is important for the sensible heat anomaly. The authors should add relevant discussion for the validity of sensible heat flux calculation in section 3.2.

The overall changes in wind speed anomaly over rainfed cropland are very small—much smaller than the changes in ΔT—however, the differing y-axis scales made this difficult to interpret. As part of including the other land cover classes, we will adjust the y-axis scales across the subplots so that the scales are identical between the different land covers, which will make the small wind speed anomalies more evident for cropland. Versions of Figures 3 and S3 with the new y-axis scales are included at the end of the responses as Figures R7 and R8. We do not consider that such relatively small changes in wind speed over rainfed cropland would have an appreciable effect on the overall sensible heat flux, given the large changes in ΔT. Changes in wind speed over grassland and shrubland are larger, but as seen in our new figures there is little difference between quartiles for these cases. For broadleaved deciduous cover, higher ΔT is associated with higher wind speed, so that both act together to increase sensible heat flux and there is no discrepancy in the ordering of events by SHF.

Line 161-162: Can authors add more clarification on how DT is calculated at 0.01° spatial resolution? What is the spatial resolution of ERA5 2m used in the study?

ERA5 T2m is provided at 0.25°, and is then bilinearly interpolated to the location of each 0.01° LST observation in order to compute ΔT. The interpolation step was included at lines 158–159 but we will modify the text there to make the process clearer:

T2m data at 0.25° resolution is taken from ERA5 reanalysis (Hersbach et al., 2020), and linearly interpolated to the overpass times of the LST observations. To enable the computation of ΔT using the 0.01° MODIS Aqua LST, the ERA5 T2m data is also bilinearly interpolated to the location of each 0.01° pixel.

Line 169-171: Provide clarity on ERA5 2m wind speed. How is it calculated?

The text contained an error here in referring to ERA5 2m wind speed: this should be ERA5 10m wind speed. The 10m wind components are simply provided in the ERA5 output. We will correct the text at line 169 to read *ERA5 10m wind speed*.

Line 206-209: The negative latent heat flux anomaly for shrubland before the onset of flash drought has been explained as transiting to water limitation regime earlier than other land covers. However, the evolution of surface soil moisture is similar for all land cover classes. There should be other factor that may explain the early negative latent heat flux anomaly. I suggest investigating the evolution of variables for shrublands as done for rainfed cropland in Figure 3.

Figure R1 shows the equivalent of Figure 3 for shrublands and we propose to include this in the revised Supplementary Information (along with the equivalent plots for the grassland and broadleaved deciduous classes). Figure R1 supports the interpretation of shrublands reaching water limitation earlier: the strongest three quartiles of events are hardly able to sustain any increase in latent heat flux relative to climatological levels, and the peak negative standardised anomalies in latent heat flux for shrubland have a much larger magnitude than for the other land cover classes.

We will add text at the end of Section 3.2 (line 275) to provide a brief comparison of the results shown for rainfed cropland in Figure 3 to the results for the additional three land cover classes:

The differences in land-atmosphere coupling between stronger and weaker events are largely the same across the four land cover classes shown in Figure 2 (see Figures S4–S9). All four classes show less of an increase in latent heat flux for the stronger events, along with worse impacts on vegetation. Differences between the quartiles at the peak of the drought are larger in pixels with broadleaved deciduous land cover (this is particularly noticeable in the atmospheric conditions, e.g. T2m). This suggests that for the weaker events (Q1 and Q2), the trees are able to buffer against the surface soil moisture deficit by accessing deeper soil moisture (Nicolai-Shaw et al., 2017), resulting in milder impacts on—for example—latent heat flux and subsequent feedbacks to air temperature, when compared with the same quartiles in other land covers, where short vegetation cannot access deeper soil moisture. Once the drought becomes severe enough, this buffer is no longer sufficient to mitigate the evaporative stress and the impacts of the drought become as intense as in the other land covers. All four land cover classes show stratification in vegetation and the surface energy budget for months before and after onset, demonstrating that the subseasonal-to-seasonal persistence is a common feature, and that precursor land surface conditions play a role in the evolution of land-atmosphere coupling for each class.

We note that the similarity of the evolution of the surface soil moisture anomaly composites between land cover classes does not indicate that the land covers must be in the same state of water limitation, which also depends on the actual (non-anomaly) value of soil moisture and the critical soil moisture threshold (at which evaporation becomes moisture limited). The critical threshold will vary between geographic locations and hence between land covers. It is therefore to be expected that differences in soil moisture relative to the critical threshold will result in the evolution of the latent heat flux anomaly evolution differing between land cover classes even when the soil moisture composites are similar. We will make this point clearer by adding text at line 209:

Note that differences in the surface energy budget between land cover classes are expected despite the soil moisture composites being similar, due to geographical variation in the critical soil moisture threshold.

We originally considered using a measure of soil moisture relative to the critical threshold to composite the droughts. However, obtaining global gridded global maps of the critical threshold is a complex process that introduces many additional assumptions (Fu *et al.*, 2022, 2024; Paul *et al.*, 2025), so we chose to interpret the water limitation through the changes in the surface energy balance instead.

Line 303-305: Please rephrase for clarity or provide additional details on the regions.

We will rephrase the text at line 303 to read:

Figure 4c shows that the regions with the strongest VOD and T2m sensitivities—such as north-eastern Brazil, southern Africa and the western USA—also do not exhibit an elevated latent heat flux anomaly after flash drought onset…

Line 310-311: The three semi-arid regions have different land cover classes. I think land cover should be brought into the discussion as there is difference in the evolution of land-atmospheric coupling process for different land cover classes (Figure 2).

The land covers in which the flash droughts occur in each of the three regions are plotted in Figure R9. It is evident from this that the East and Southern Africa regions have a very similar distribution of land covers for the events, despite East Africa showing significant results for the precursor VOD/maximum air temperature coupling and Southern Africa not. We also note that whilst it is true that the evolution of land-atmosphere coupling varies between land cover classes, the behaviour is in fact very similar across the classes in the critical ways required for the analysis in this section: all classes show a decrease in latent heat flux and an increase in ΔT around drought onset, the events in all classes are associated with elevated air temperatures, and all classes show stratification in VOD conditions prior to the observed decrease in surface soil moisture. This will be more apparent in the revised manuscript due to the inclusion of the ΔT-stratified plots for the additional land covers in response to the comments above. We therefore do not see any evidence that land cover is a major driver of the differences in results found between the regions.

Line 351-355: These sentences suggests that study lacks substantial conclusion as per the objective set in the introduction. I suggest discussing the role of different land cover classes for non-robust relationship between precursor variable and 2m anomalies. Further, the role of VOD as precursor need to be assessed for other key regions to have robust conclusion.

We will edit both the framing of the objectives in the introduction and the final conclusions, in order to make the relevance of our results for S2S predictability clearer. We believe that demonstrating the persistence on monthly timescales of land surface anomalies associated with stronger flash droughts (Figure 3) and showing that land surface satellite observations can contain relevant information for flash drought heat extremes months ahead (Section 3.4), is of key importance for informing the future development of S2S forecasts for flash drought. We promote a focus on improving the representation of vegetation in S2S models, as well as further evaluation of how soil moisture is initialised relative to the critical threshold in these forecasts. The results of this paper provide strong evidence that the land surface contains information on the correct timescales to be of use to S2S forecasts, rather than all the skill being derived from the precipitation forecast. This means that it is realistic to expect that shortcomings in land surface representation make a significant contribution to the current poor performance of dynamical S2S forecasts of flash drought, so that improvements could be of real benefit.

We propose to rephrase the objective in the introduction at lines 81–84 to be more realistic and specific to the work performed in the manuscript:

Overall, this work aims to understand how satellite observations can be exploited to ~~monitor and predict flash drought conditions~~ understand land-atmosphere coupling during flash droughts globally, and to ascertain which variables contain useful information ~~to aid~~ on the timescales relevant to S2S forecasts whilst also being relatively convenient to observe.

We will add to the end of Section 3.4 (line 355) to emphasise the implications of precursor VOD demonstrating the ability to provide information on air temperature anomalies with such long lead times. We acknowledge that our study does not include other key flash drought regions around the world in this section of the results, so this text will also make it clearer that this is a proof-of-concept approach to demonstrate that land surface observations can provide relevant information at S2S-relevant lead times, rather than a globally robust monitoring/forecasting method:

However, the clear influence of precursor VOD on peak air temperatures in both West and East Africa, with a lead time of 1–2 months, provides a proof of concept that satellite observations of the land surface can provide information on potential flash drought impacts at timescales relevant for S2S forecasting.

We have added more detail on why the three African regions were selected at line 312 in response to a comment from Reviewer 2 (briefly: it is particularly important to understand how satellite observations can best be utilised in regions like these, which have very sparse in situ observations).

Finally, we will refine the text in the discussion at lines 408–421 to clarify how the results of the study feed into current knowledge and approaches to S2S forecasts of flash drought:

*This work highlights the importance of correctly representing the land surface and its feedbacks to the atmosphere in S2S forecasting models to enable the prediction of flash drought impacts. ~~Our findings~~ Since we have shown that drier land precursor conditions are associated with stronger flash droughts and a higher risk of heat extremes, via their effect on the surface energy balance, shortcomings in the initialisation of these precursors and the modelling of the surface energy balance are likely to be major reasons for the current poor performance of dynamical S2S forecasts. This is consistent with ~~previous results showing~~ the findings of DeAngelis et al. (2020), who showed that correct soil moisture initialisation during dry conditions is a key contributor to the predictability of flash droughts in ~~these~~ **S2S** models. ~~(Deangelis et al., 2020). Further assessment of land-atmosphere coupling is required to understand how model parameterisations impact flash drought prediction skill.~~*

~~Most currently operational S2S forecast models lack interactive vegetation, which is likely to lead to deficiencies in their representation of the surface energy budget. Benson and Dirmeyer (2023) also found that S2S models do not accurately reproduce the link between dry soil moisture and temperature extremes, highlighting the importance of soil moisture being~~ Deficiencies in the representation of the surface energy budget frequently occur in S2S models when soil moisture is not initialised on the correct side of critical land-atmosphere coupling thresholds, leading to a poor simulation of the link between dry soil moisture and temperature extremes (Benson and Dirmeyer, 2023). This is a crucial issue for flash drought forecasting: we found that for stronger flash droughts, the soil is closer to water limitation, or already water-limited, when the major precipitation deficit occurs. If the soil moisture is poorly initialised in a model, or the representation of the water limitation threshold is erroneous, then the modelled evolution towards water limitation will inaccurately predict the strength of the flash drought, with corresponding errors in the impacts on vegetation and air temperature. Depending on the anomaly magnitudes involved for a particular event, this could also affect whether an event reaches the required threshold to qualify as a flash drought. Poor simulation of the surface energy budget is also likely to be caused by the lack of interactive vegetation in most currently operational S2S forecast models, which will impact forecasts of evapotranspiration and soil moisture.

Our results therefore motivate further development and evaluation of land-atmosphere coupling in dynamical S2S forecasts, including the introduction of dynamic vegetation models and assessment of critical soil moisture thresholds, to understand how changes to model parameterisations can improve flash drought prediction skill. Further investigation into the assimilation of land surface data into models would also be valuable: Ahmad et al. (2022) showed that assimilation of soil moisture and Leaf Area Index improved the ability of a land surface model to capture the impacts of flash droughts, but did not investigate the consequences for S2S predictability.

Clearly, land surface information...

Line 403: If VOD is closely linked to root zone soil moisture (RZSM) and serves as a precursor for 2m temperature anomalies during flash droughts, does identifying flash droughts based solely on surface soil moisture provide a reliable approach for flash drought monitoring? Further, I suggest using ESA-CCI-COM based root zone soil moisture dataset in addition to GLEAM RZSM and discuss its application for land atmosphere interaction during flash drought.

In terms of successfully monitoring whether a flash drought is occurring in real time, our results suggest that surface soil moisture is reliable: the rapid decrease in surface soil moisture is concurrent with the rapid decreases in RZSM and SESR, according to Figure 3. However, information from other land surface variables (e.g. VOD, or RZSM) can provide additional detail on the severity of impacts, including predictability on a subseasonal-to-seasonal timescale, which surface soil moisture is unable to capture (remembering that the quality of any subseasonal prediction will also depend on the precipitation forecast). We would therefore advocate for monitoring both surface soil moisture and VOD. We will add this to the discussion at line 405:

The persistence of these vegetation effects means that satellite observations of vegetation can provide subseasonal predictability for flash drought impacts, so it is beneficial to monitor vegetation condition in addition to surface soil moisture.

During the study, we did investigate the possibility of analysing ESA CCI RZSM for inclusion in Figure 3 in addition to GLEAM RZSM. However, we found that we could not see any stratification in ESA CCI RZSM between ΔT quartiles, as a result of it being very tightly constrained by the ESA CCI SM data (Figure 3g), because ESA CCI RZSM is obtained by only applying a temporal filter to the surface soil moisture, while likely losses through evapotranspiration are neglected. Since the flash droughts are identified using ESA CCI SM, this places constraints on the resulting composites of ESA CCI SM (Figure 3g; as mentioned at lines 247–248). For example, due to the defined method of identification, it is guaranteed that the surface soil moisture composites will decrease below a standardised anomaly of -1. These constraints then feed through to ESA CCI RZSM, so that there artificially appears to be very little spread in its behaviour between quartiles. Further work confirmed that this was not an issue with the ESA CCI RZSM data itself: if GLEAM surface soil moisture is used to define the flash droughts instead, then ESA CCI RZSM shows the expected spread across quartiles. We therefore elected not to include ESA CCI RZSM in the manuscript since the results would be mostly related to the specifics of the identification methodology than due to anything physically interesting occurring in the data.

Reviewer 2

The authors present a study that uses remote sensing data (supplemented with reanalysis data) to characterize dynamics of the surface energy balance during flash drought events. They also look at other remotely sensed data, including vegetation optical depth, to investigate how they change with respect to drought strength as characterized by ΔT anomaly. Overall, there is a high need to assess drought globally and to improve predictability and the topic is well within the scope of HESS.

Major comments

1. *Overall, the manuscript is well written but could benefit from some reorganization: The results section contains considerable portions of methodology (e.g. Sections 3.2, 3.3). It would be good to explore whether this can be moved into the methodology section to improve readability of the manuscript.*

We will restructure the manuscript to bring more of the methodology into Section 2.

From Section 3.2, we will move lines 231–239 to the end of Section 2.2, with modifications to improve the flow of the text in its new position:

In addition to compositing over all flash droughts occurring in a given land cover class, we compare the evolution of events with differing strengths of land-atmosphere coupling. This is done by stratifying the events based on their maximum value of ΔT during the drought. Events in which the land surface becomes more highly water-stressed will exhibit a larger standardised anomaly of ΔT at the peak of the drought, due to the surface energy balance becoming partitioned more towards sensible heat flux than latent heat flux. ~~In this section we focus on flash droughts during all months in rainfed cropland.~~ For each flash drought event, we take the time series of the standardised anomaly in ΔT (computed using MODIS Aqua LST) around the onset date, apply a 5-day rolling mean smoothing, then find the maximum value of this anomaly in days 0–20 after onset, $(\Delta T)_{max}$. The flash droughts are then separated into quartiles based on $(\Delta T)_{max}$, so that quartile 1 (Q1) contains the weakest (least evaporatively stressed, i.e. smallest $(\Delta T)_{max}$) flash droughts, and Q4 the strongest (most evaporatively stressed, i.e. largest $(\Delta T)_{max}$).

The results in Section 3.2 will then begin:

We now explore how the evolution of land-atmosphere variables during flash droughts varies depending on the strength of the surface flux response, as quantified by $(\Delta T)_{max}$.

Similarly, for Section 3.3 we will move the methodology from lines 282–295 to the end of Section 2.2, with minor modifications:

~~Using~~ To obtain a global, spatially-varying picture of the sensitivity of variables to the decrease in soil moisture associated with flash droughts, we use events computed at the 0.25° scale as before, ~~we~~ but composite around all events in each 2.5° grid box globally. This resolution is…

Lines 279–280 in Section 3.3 will then be modified to:

We now explore the spatial variation in flash drought impacts globally, by investigating the sensitivity of vegetation (in terms of VOD) and 2m air temperature to the decrease in surface soil moisture during flash droughts, as defined in Equation 3.

We also considered whether to move anything from Section 3.4, but the additional methodology required in this section is minimal so we decided this section is more readable as is.

2. Science questions: This study presents as a proof of concept for quantifying surface energy balance changes during drought. There are limited additional results (e.g. the relationship between VOD and drought). For me, this is OK, but the manuscript would benefit from additional justification for the choices of region and land-cover in results and additional discussion about approaches for applying this method in S2S forecasting or drought monitoring.

With regard to land cover, rather than only investigating a single land cover class in detail in Section 3.2/Figure 3, we will now include results from the other three land cover classes with the highest numbers of flash droughts, in response to comments from Reviewer 1.

In addition to being regions where the importance of land-atmosphere coupling is well established, a major motivation for choosing the three African regions in Section 3.4 was that exploring the potential of satellite monitoring is particularly important in regions with a lack of ground-based in situ observations. In situ observations of variables such as precipitation (Dezfuli *et al.*, 2017), soil moisture (Albergel *et al.*, 2012) and 2m temperature (Balsamo *et al.*, 2018) are much sparser across Africa than other flash drought-prone regions such as western Europe or the central/eastern US. Satellite remote sensing and reanalysis or model data are the only realistic options for developing a drought monitoring or prediction system in this case (Anderson *et al.*, 2012). We will add text to the beginning of Section 3.4 (line 312) to highlight this:

The regions and their respective seasons are shown in Figure 5a. In addition to having strong land-atmosphere coupling, we choose to focus on these regions as case studies because they have sparse in situ observations of land surface and meteorological variables (Albergel et al., 2012; Dezfuli et al., 2017; Balsamo et al., 2018), so it is particularly important to understand how satellite remote sensing data could inform drought monitoring or prediction.

The discussion section from lines 408–421 will be edited to clarify the applications of our findings for S2S forecasting: these changes are described in full in response to a similar comment from Reviewer 1.

3. Land-atmosphere interactions: I am not sure whether I agree with the author that this manuscript is primarily about land-atmosphere interactions as is indicated by the title. The manuscript mainly addresses surface energy balance, which is important enough. I suggest that the title is changed to something less broad. The main LA interaction discussed here is the relationship between Tair and Tsoil, which is part of the method (e.g. delta T), but since delta T is taken from reanalysis and delta T anomalies are discussed, it is not really explored in depth. I am also questioning the use of the word feedback (see specific comment)

We have considered the title carefully in light of this suggestion and concluded that the original title remains appropriate.

In other papers focused on flash droughts, the phrases “land-atmosphere interactions”, “land-atmosphere coupling”, or “land-atmosphere feedback” are commonly used to refer to the interplay between soil moisture/vegetation/surface fluxes/atmospheric conditions (e.g. DeAngelis *et al.*, 2020; Christian *et al.*, 2021; Fu & Wang, 2023). We include variables across these domains in our analysis (although we acknowledge that not all of them are truly observations), including near-surface air temperature and VPD, precipitation, vegetation water content and soil moisture, in addition to the components of the surface energy balance. We therefore feel that the existing title is the best representation of where our work fits within the wider flash drought literature. Whilst it is true that the some of our main results are focused on the surface energy balance, this is because the fluxes involved are what mediates the relationships between the atmospheric variables and the land surface variables and therefore have a large impact on how land-atmosphere coupling influences the development of flash droughts, rather than because we are only interested in the surface energy balance itself. We do not feel that a more specific title focused on the surface energy balance would cover the results in sections 3.3 or 3.4, or parts of 3.2. We go into more detail on the use of the word "feedback" in response to the specific comment below, including how we will change the text to clarify the mechanism of the land-atmosphere feedback.

Specific comments:

L215: "Although net radiation is decreasing, the land has entered a water-limited regime, so this radiation drives less evaporation" > I am not sure about the conjunction although here. Is that not something that would be expected.

We agree that this wrongly suggested that the decrease in evaporation was unexpected—we intended to say that the increase in ΔT was unexpected (or rather, cannot be explained without accounting for water limitation being reached) when net radiation is decreasing. We will rephrase lines 214–217 to read:

However, despite the decrease in R_n, ΔT continues to increase. This is a result of the surface energy balance (Equation 1) becoming partitioned more towards sensible heat flux, because the land has entered a water-limited regime, so the radiation drives less evaporation. This is consistent with the decline in latent heat flux shown by GLEAM at this stage.

Fig 3: Provide explanation of variable abbreviations in figure caption

We will rewrite the caption as:

Figure 3. Evolution of land-atmosphere variables during flash droughts, composited over all events in rainfed cropland during the period 2000–2020. Each panel splits the events into quartiles based on the maximum ΔT *anomaly (computed as the difference between MODIS Aqua LST and ERA5 T2m) 0–20 days after onset. All composites have been smoothed with a 10-day running mean. Abbreviated variable names are: Land Surface Temperature (LST), 2m air temperature (T2m), latent heat flux (LHF), net radiation at the surface (Rn), downwelling shortwave radiation at the surface (downwelling SW), surface soil moisture (SM), root-zone soil moisture (RZSM), Standardised Evaporative Stress Ratio (SESR), Vegetation Optical Depth (VOD), and Solar Induced Fluorescence (SIF).*

L176: "We investigate feedbacks from flash droughts to atmospheric temperatures using composites of ERA5 daily maximum 2m air temperature (T2m)" > I am not sure what is referred to here as feedback since the study looks at Ts -> T2m, which is not a feedback but maybe a forcing?

We view this as a feedback because the increase in T_s (and in ΔT) during flash droughts is itself influenced by air temperatures via their control on evaporative demand. Warmer near-surface air leads to higher evaporative demand; during the early stages of flash drought development, if water limitation has not yet been reached, this increases evaporation and accelerates the drying of the soil. Once the soil becomes water stressed, sensible heat flux increases in place of evaporation, which is associated with increases in T_s and ΔT. Describing the effect of ΔT on T2m as a forcing would imply that T2m itself has no influence on the value of T_s reached during the flash drought, which is untrue. T2m influences the evolution of T_s, which in turn influences T2m via the sensible heat flux. It is well established for the coupling between land surface and atmospheric conditions to be referred to explicitly as a feedback in studies of flash drought (Pendergrass *et al.*, 2020; Christian *et al.*, 2021; Qing *et al.*, 2022; Fu & Wang, 2023; Lesinger *et al.*, 2024), as well as in studies of drought on longer timescales (Miralles *et al.*, 2019; Dirmeyer *et al.*, 2021). We therefore propose to retain the "feedback" terminology in the revised manuscript. We will also clarify the mechanisms linking the land and atmosphere, so that it is more obvious why referring to a feedback is appropriate, by adding text at line 309:

Section 3.3 showed that VOD and T2m are generally most sensitive to flash drought in semi-arid regions, and suggested that the water-limited conditions in these areas promote land-atmosphere feedbacks that are responsible for the larger increases in T2m standardised anomalies. Positive anomalies in T2m are associated with increased evaporative demand. This accelerates the loss of soil moisture via evaporation until water limitation is reached, at which point the sensible heat flux increases, resulting in a positive feedback to T2m.

References

Ahmad, S. K., Kumar, S. v., Lahmers, T. M., Wang, S., Liu, P., Wrzesien, M. L., Bindlish, R., Getirana, A., Locke, K. A., Holmes, T. R., & Otkin, J. A. (2022). Flash Drought Onset and Development Mechanisms Captured With Soil Moisture and Vegetation Data Assimilation. *Water Resources Research*, *58*(12). https://doi.org/10.1029/2022WR032894

Albergel, C., de Rosnay, P., Gruhier, C., Muñoz-Sabater, J., Hasenauer, S., Isaksen, L., Kerr, Y., & Wagner, W. (2012). Evaluation of remotely sensed and modelled soil moisture products using global ground-based in situ observations. *Remote Sensing of Environment*, *118*, 215–226. https://doi.org/10.1016/J.RSE.2011.11.017

Anderson, W. B., Zaitchik, B. F., Hain, C. R., Anderson, M. C., Yilmaz, M. T., Mecikalski, J., & Schultz, L. (2012). Towards an integrated soil moisture drought monitor for East Africa. *Hydrology and Earth System Sciences*, *16*(8), 2893–2913. https://doi.org/10.5194/HESS-16-2893-2012

Balsamo, G., Agusti-Panareda, A., Albergel, C., Arduini, G., Beljaars, A., Bidlot, J., Bousserez, N., Boussetta, S., Brown, A., Buizza, R., Buontempo, C., Chevallier, F., Choulga, M., Cloke, H., Cronin, M. F., Dahoui, M., Rosnay, P. de, Dirmeyer, P. A., Drusch, M., … Zeng, X. (2018). Satellite and In Situ Observations for Advancing Global Earth Surface Modelling: A Review. *Remote Sensing, 10*(12), 2038. https://doi.org/10.3390/RS10122038

Benson, D. O., & Dirmeyer, P. A. (2023). The Soil Moisture–Surface Flux Relationship as a Factor for Extreme Heat Predictability in Subseasonal to Seasonal Forecasts. *Journal of Climate*, *36*(18), 6375–6392. https://doi.org/10.1175/JCLI-D-22-0447.1

Christian, J. I., Basara, J. B., Hunt, E. D., Otkin, J. A., Furtado, J. C., Mishra, V., Xiao, X., & Randall, R. M. (2021). Global distribution, trends, and drivers of flash drought occurrence. *Nature Communications*, *12*(1), 1–11. https://doi.org/10.1038/s41467-021-26692-z

DeAngelis, A. M., Wang, H., Koster, R. D., Schubert, S. D., Chang, Y., & Marshak, J. (2020). Prediction Skill of the 2012 U.S. Great Plains Flash Drought in Subseasonal Experiment (SubX) Models. *Journal of Climate*, *33*(14), 6229–6253. https://doi.org/10.1175/JCLI-D-19-0863.1

Dezfuli, A. K., Ichoku, C. M., Huffman, G. J., Mohr, K. I., Selker, J. S., van de Giesen, N., Hochreutener, R., & Annor, F. O. (2017). Validation of IMERG Precipitation in Africa. *Journal of Hydrometeorology*, *18*(10), 2817–2825. https://doi.org/10.1175/JHM-D-17-0139.1

Dirmeyer, P. A., Balsamo, G., Blyth, E. M., Morrison, R., & Cooper, H. M. (2021). Land-Atmosphere Interactions Exacerbated the Drought and Heatwave Over Northern Europe During Summer 2018. *AGU Advances*, *2*(2). https://doi.org/10.1029/2020AV000283

Fu, K., & Wang, K. (2023). Contributions of Local Land–Atmosphere Coupling and Mesoscale Atmospheric Circulation to the 2013 Extreme Flash Drought and Heatwave Compound Event Over Southwest China. *Journal of Geophysical Research: Atmospheres*, *128*(21), e2023JD039406. https://doi.org/10.1029/2023JD039406

Fu, Z., Ciais, P., Feldman, A. F., Gentine, P., Makowski, D., Prentice, I. C., Stoy, P. C., Bastos, A., & Wigneron, J.-P. (2022). Critical soil moisture thresholds of plant water stress in terrestrial ecosystems. *Science Advances*, *8*(44), 7827. https://doi.org/10.1126/SCIADV.ABQ7827

Fu, Z., Ciais, P., Wigneron, J.-P., Gentine, P., Feldman, A. F., Makowski, D., Viovy, N., Kemanian, A. R., Goll, D. S., Stoy, P. C., Prentice, I. C., Yakir, D., Liu, L., Ma, H., Li, X., Huang, Y., Yu, K., Zhu, P., Li, X., … Smith, W. K. (2024). Global critical soil moisture thresholds of plant water stress. *Nature Communications 2024 15:1*, *15*(1), 1–13. https://doi.org/10.1038/s41467-024-49244-7

Lesinger, K., Tian, D., & Wang, H. (2024). Subseasonal Forecast Skill of Evaporative Demand, Soil Moisture, and Flash Drought Onset from Two Dynamic Models over the Contiguous United States. *Journal of Hydrometeorology*, *25*(7), 965–990. https://doi.org/10.1175/JHM-D-23-0124.1

Lovino, M. A., Pierrestegui, M. J., Müller, O. v., Müller, G. v., & Berbery, E. H. (2024). The prevalent life cycle of agricultural flash droughts. *Npj Climate and Atmospheric Science 2024 7:1*, *7*(1), 1–11. https://doi.org/10.1038/s41612-024-00618-0

Miralles, D. G., Gentine, P., Seneviratne, S. I., & Teuling, A. J. (2019). Land–atmospheric feedbacks during droughts and heatwaves: state of the science and current challenges. *Annals of the New York Academy of Sciences*, *1436*(1), 19–35. https://doi.org/10.1111/nyas.13912

Nicolai-Shaw, N., Zscheischler, J., Hirschi, M., Gudmundsson, L., & Seneviratne, S. I. (2017). A drought event composite analysis using satellite remote-sensing based soil moisture. *Remote Sensing of Environment*, *203*, 216–225. https://doi.org/10.1016/J.RSE.2017.06.014

Paul, S., Feldman, A. F., & Karthikeyan, L. (2025). Global Patterns of Critical Soil Moisture and Seasonal Hydrological Regimes Derived From Soil Moisture and Diurnal Soil Temperature Range. *Water Resources Research*, *61*(7). https://doi.org/10.1029/2024WR037998

Pendergrass, A. G., Meehl, G. A., Pulwarty, R., Hobbins, M., Hoell, A., AghaKouchak, A., Bonfils, C. J. W., Gallant, A. J. E., Hoerling, M., Hoffmann, D., Kaatz, L., Lehner, F., Llewellyn, D., Mote, P., Neale, R. B., Overpeck, J. T., Sheffield, A., Stahl, K., Svoboda, M., … Woodhouse, C. A. (2020). Flash droughts present a new challenge for subseasonal-to-seasonal prediction. *Nature Climate Change, 10*(3), 191–199. https://doi.org/10.1038/s41558-020-0709-0

Qing, Y., Wang, S., Ancell, B. C., & Yang, Z. L. (2022). Accelerating flash droughts induced by the joint influence of soil moisture depletion and atmospheric aridity. *Nature Communications*, *13*(1), 1–10. https://doi.org/10.1038/s41467-022-28752-4

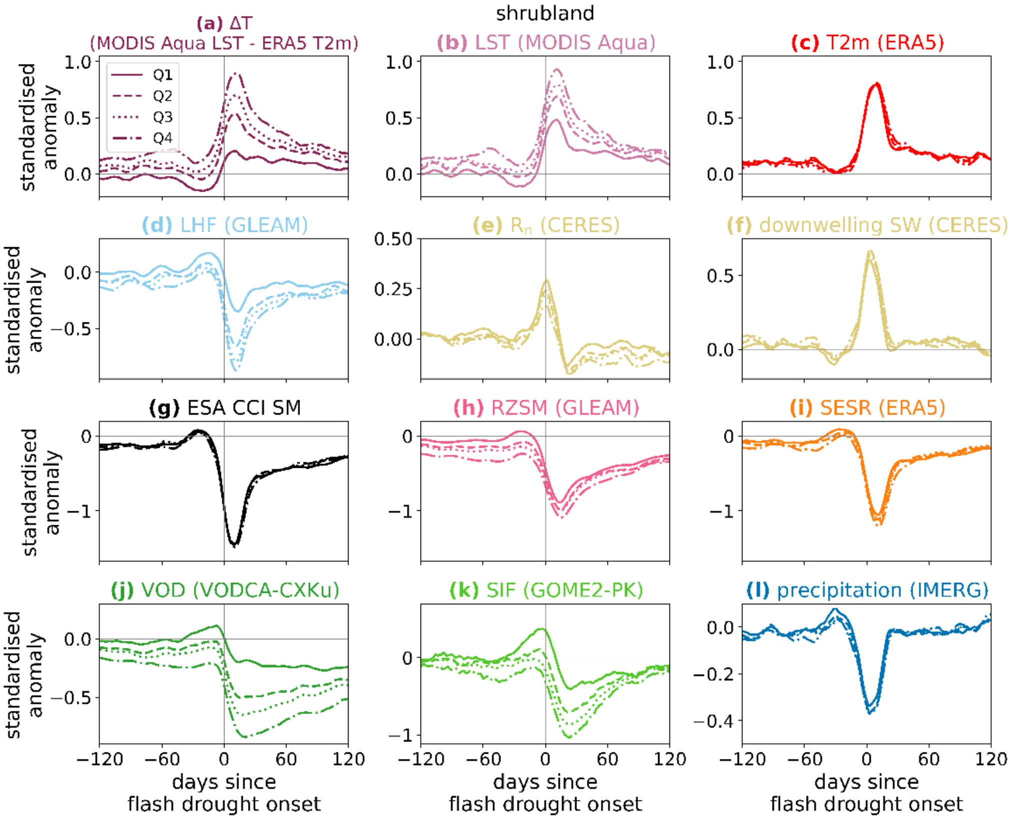

Figure R1: Evolution of land-atmosphere variables during flash droughts as in Figure 3, but for all events occurring in shrubland.

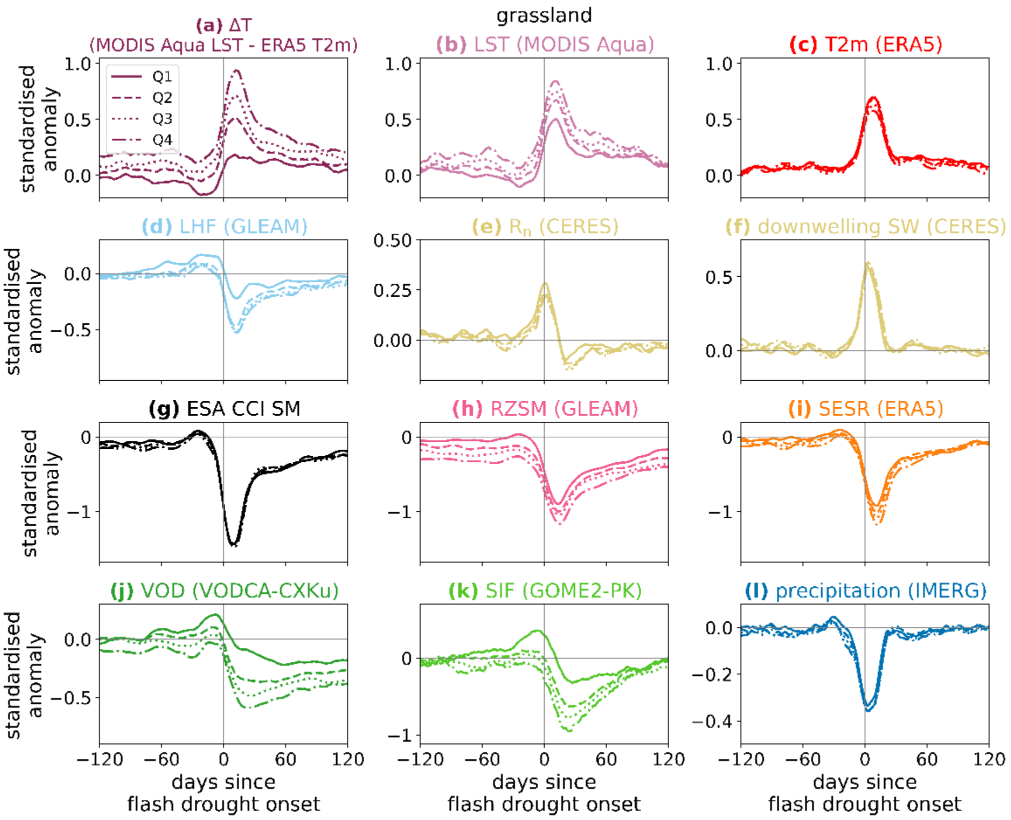

Figure R2: Evolution of land-atmosphere variables during flash droughts as in Figure 3, but for all events occurring in grassland.

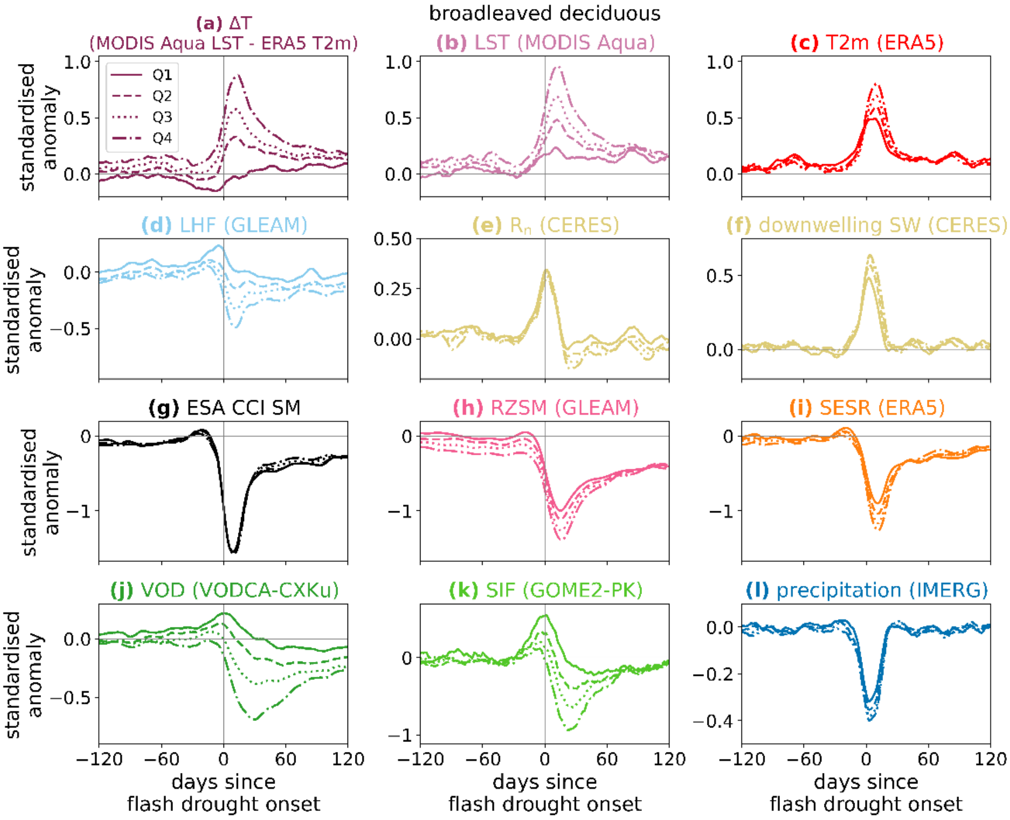

Figure R3: Evolution of land-atmosphere variables during flash droughts as in Figure 3, but for all events occurring in broadleaved deciduous tree cover.

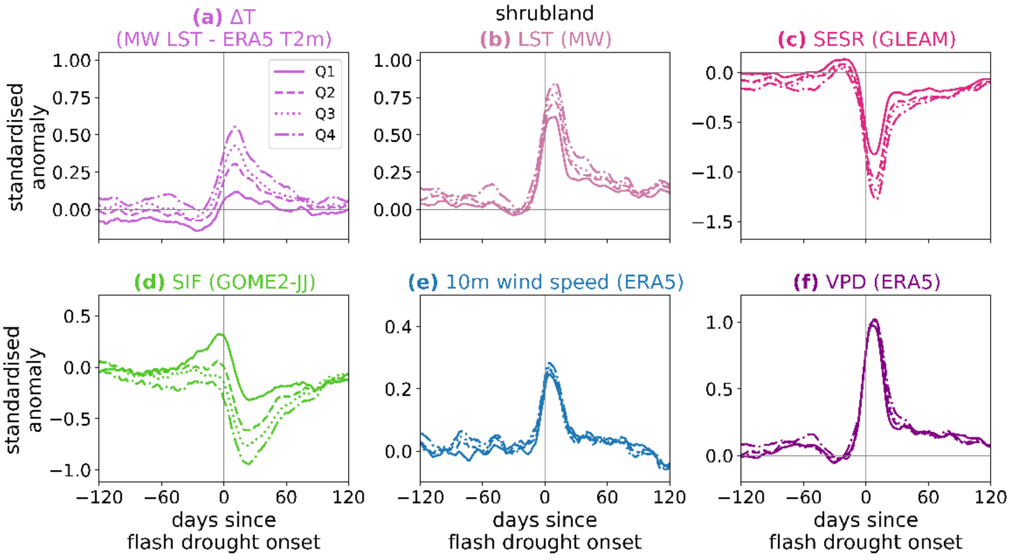

Figure R4: Additional variables to accompany Figure R1 (shrubland).

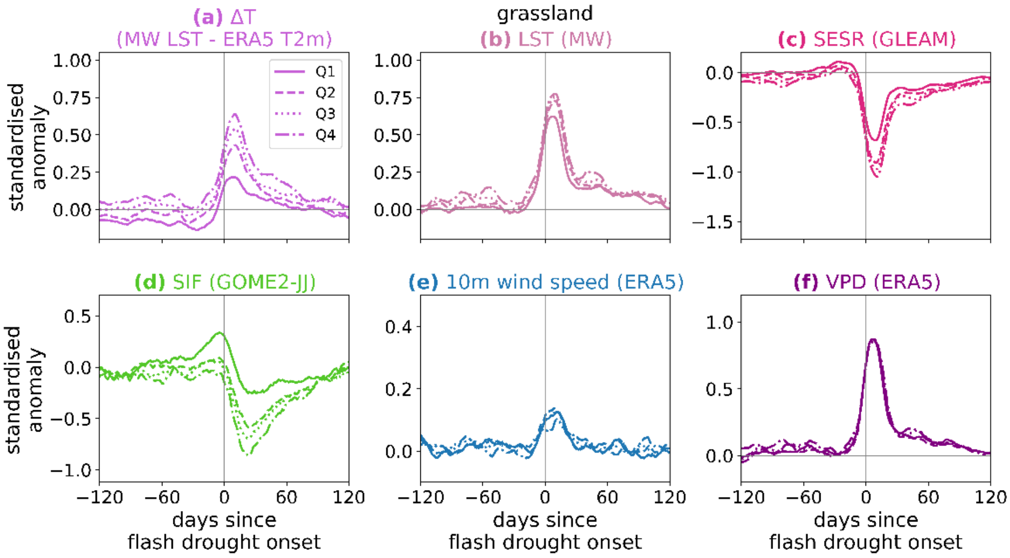

Figure R5: Additional variables to accompany Figure R2 (grassland).

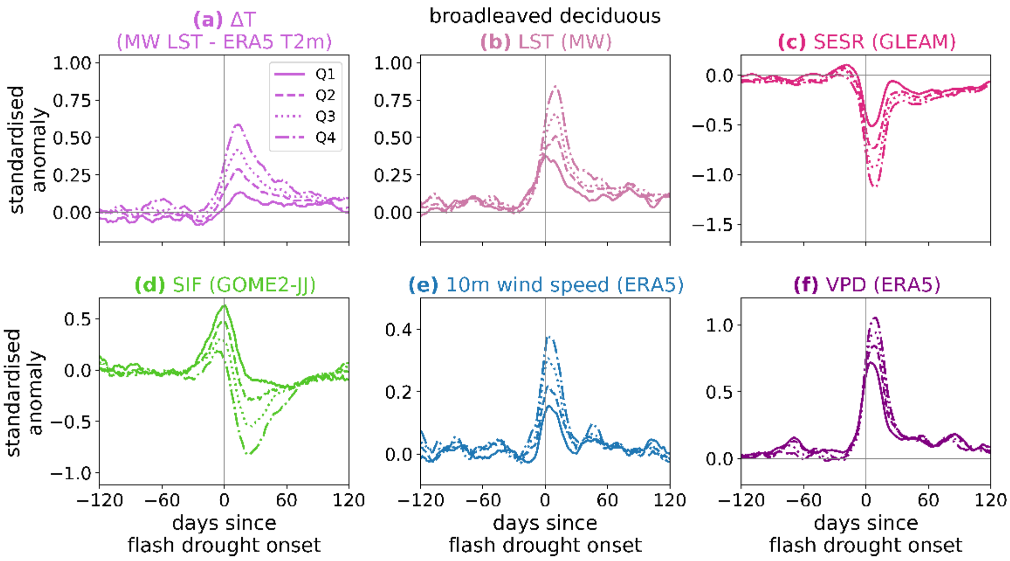

Figure R6: Additional variables to accompany Figure R3 (broadleaved deciduous).

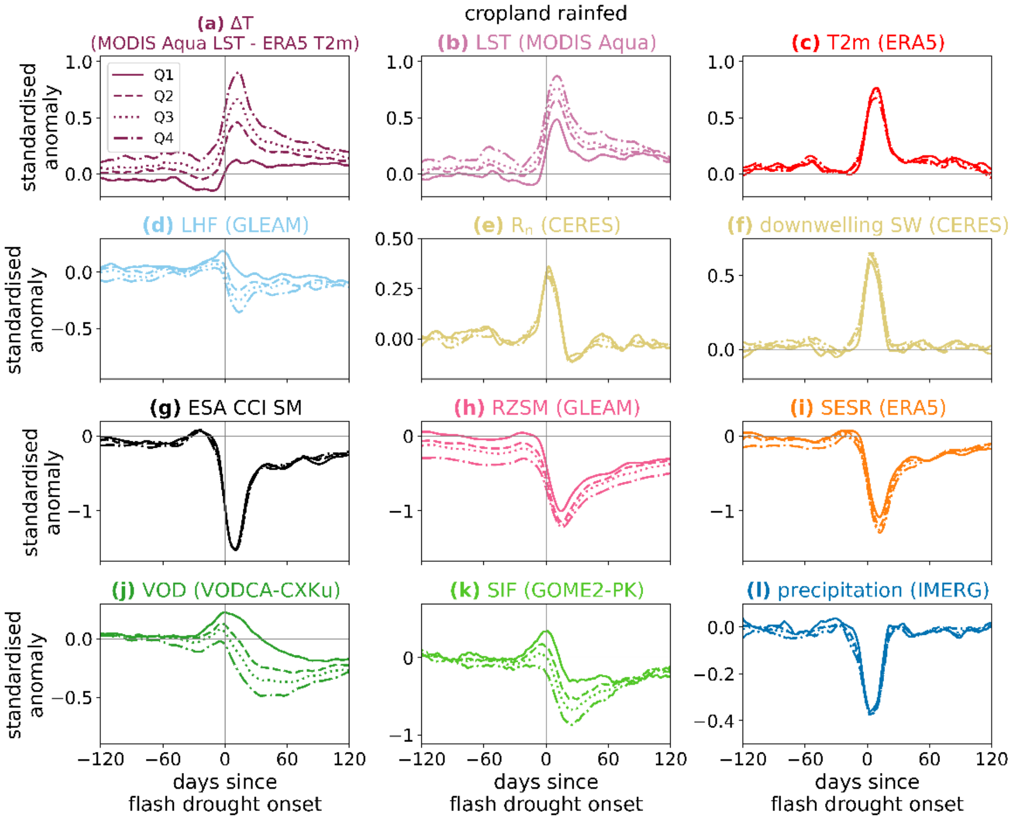

Figure R7: New version of Figure 3, with y-axes matching the other land cover classes from Figures R1–R3.

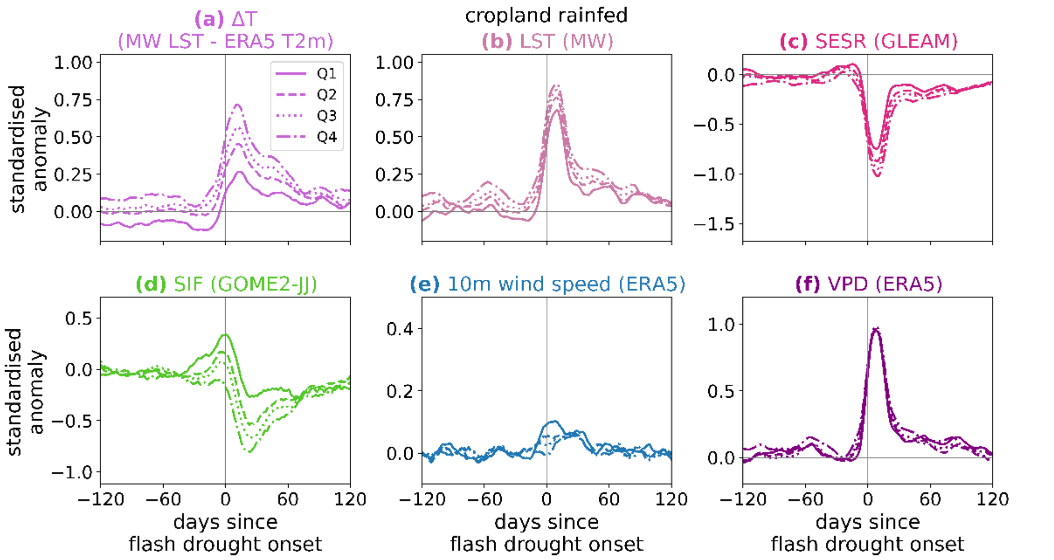

Figure R8: New version of Figure S3, with y-axes matching the other land cover classes from Figures R4–R6.

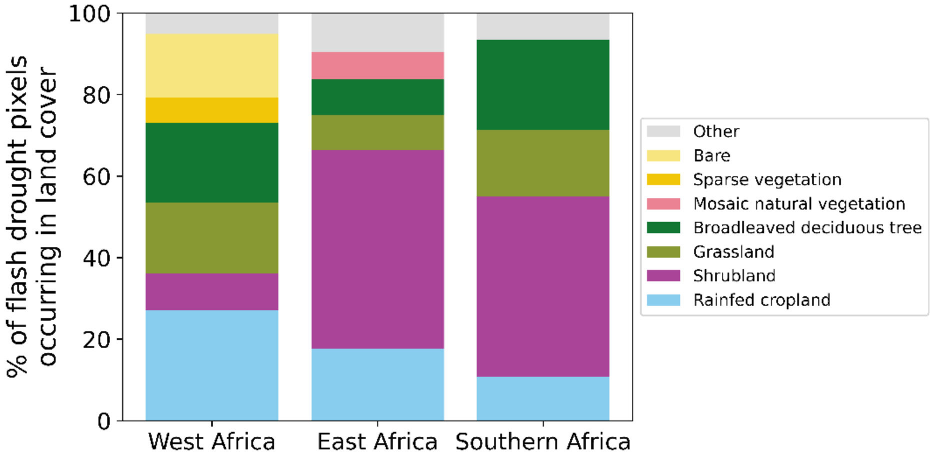

Figure R9: Percentage of total flash droughts occurring in each land cover class, for the regions studied in Section 3.4.