<u>Response to RC2</u>

General comments

This manuscript presents the first systematic assessment of present-day and future hydrological transitions (between wet and dry extremes) across the UK. It sufficiently identifies the current gap in the literature and sets out to address this gap in a scientifically coherent and robust way, sufficiently addressing a relevant scientific question within the scope of HESS. It presents a novel approach using existing datasets and adopts scientifically robust methodologies that are reproducible, and generally states valid methods and assumptions, with possible minor additions (S1). The findings and conclusions are substantial and the results generally support the conclusions made, albeit these could be further refined with minor amendments (S2). The title clearly reflects the contents of the paper, however it could be improved to mention the analysis of meteorological transitions as well as hydrological transitions, for clarity (S3). The overall presentation of the methods and results is clear and well structured; however, some minor clarifications/amendments could substantially improve the coherence of the results (S1). The number and quality of references is appropriate, and supplementary material is provided; however, this could include additional code/datasets/catalogue of results (S1).

We would like to thank the reviewer for their comments and feedback on how our manuscript can be improved further. Please see below our detailed responses.

Specific comments

S1: Methods and assumptions, reproducibility

- Equations and definitions (or references to literature where they are defined) could be added for the calculation of the standardised indices, the fitted distributions, and for the four-transition metrics themselves (duration, magnitude, intensity, frequency).

  The calculation of SPI and SSI are well established in the literature. The literature behind the SPI is already cited in the original manuscript (i.e. Mckee et al., 1993). We will point readers to a few more recent examples highlighting the challenge of identifying the most appropriate candidate distribution for calculating SPI (e.g. Stagge et al., 2015; Vicente-Serrano et al., 2025). Whilst the gamma distribution as used in this study is widely employed globally and is regularly recommended for SPI calculation, we will add a caution in the revised manuscript that individual SPI values may change if a different distribution is used but the overall message of the paper at long climate change timescales is unlikely to change.

  The SSI was fitted with the Tweedie distribution and we have already referenced Svensson et al. (2017) in the original manuscript which carried out a robust intercomparison between different candidate distributions across UK catchments and recommends the use of the Tweedie distribution. We will recommend in the revised manuscript that whilst the Tweedie distribution is shown to provide the best fit at UK catchments, any future application of SSI using new datasets or for rivers in other regions should verify their goodness-of-fit before application.

  Each transition metric is defined in detail when they are first introduced in the manuscript (L220) and illustrated in the schematic (Figure 3), we therefore do not feel the need to expand on this further by including equations for relatively simple calculations.

- L179: "By extending our methodology to include calculating SSI, we reduce model differences in comparison to transitions identified from raw modelled flows." There are both benefits and disbenefits to using raw modelled time series versus standardised indices. These should be explained here and the choice of SSI appropriately justified. Assumptions inherent to the use of standardised indicators, in particular, temporally stationary distribution parameters, should be stated explicitly as a potential limitation. The SSI/SPI parameters are calibrated on 1982–2018 and applied through to 2080 under RCP8.5. If winters become wetter and summers drier, citing Hannaford et al. (2025), then under a fixed baseline, future winter SSI-3 will drift systematically positive and summer SSI-3 systematically negative, even with no change whatsoever in variability. The fixed baseline is a defensible choice, arguably the right one for water-management, but the authors could either provide a diagnostic separating the mean-shift contribution from the variability contribution (e.g. recomputing transitions with a transient/moving-window standardisation and comparing frequency, duration and seasonality against the fixed-baseline results), or state explicitly in the Discussion what a fixed baseline can and cannot demonstrate.

  As we aim to compare changes in transitions in the future against the current period, in context of the current infrastructure for water resources, we feel that a fixed baseline is the appropriate choice. We will add to our discussion to include this justification, and also include the concerns raised here.

- L183: "SPI...was fitted with the standard gamma distribution instead". Can the authors provide justification or a reference for this methodological decision?

  The literature behind the SPI is already cited in the original manuscript which recommends the use of the gamma distribution (i.e. Mckee et al., 1993). We will point readers to a few more recent examples highlighting the challenge of identifying the most appropriate candidate distribution for calculating SPI (e.g. Stagge et al., 2015; Vicente-Serrano et al., 2025). Whilst the gamma distribution as used in this study is widely employed globally and is regularly recommended for SPI calculation, we will add a caution in the revised manuscript that individual SPI values may change if a different distribution is used but the overall message of the paper at long climate change timescales is unlikely to change.

- L185: "we use the 3-month accumulation period (SPI-3 and SSI-3) to focus on meteorological and hydrological transitions at a seasonal time scale". Can the authors provide justification for the choice of a 3-month accumulation period? Has a sensitivity analysis with other accumulation periods (e.g. SPI-1/SSI-1, SPI-6/SSI-6) been undertaken? Given how central the accumulation period is to all subsequent transition counts and durations, this would strengthen the methodological choice.

  We chose to focus on the 3-month accumulation period as this best represents the seasonal scale transitions we are interested in for water resources. The 3-month accumulation is also commonly used in the literature for seasonal transitions e.g. Swain et al. (2025) and Chen and Wang (2022) use SPEI-3, Li et al. (2023) and Steensen et al. (2025) use SPI-3. In our initial analysis we assessed the sensitivity of transition metrics to SSI accumulation period using 1- and 6-month accumulations in addition to 3-month but found the mean transition characteristics to be broadly similar (other than the number of transition events detected, which is higher for the lower accumulations as these are a less smoothed timeseries; see below Figures R1 and R2) and so chose not to include these in the manuscript to avoid having too many figures distracting from the main results. We will however add the below plots to the supplementary.

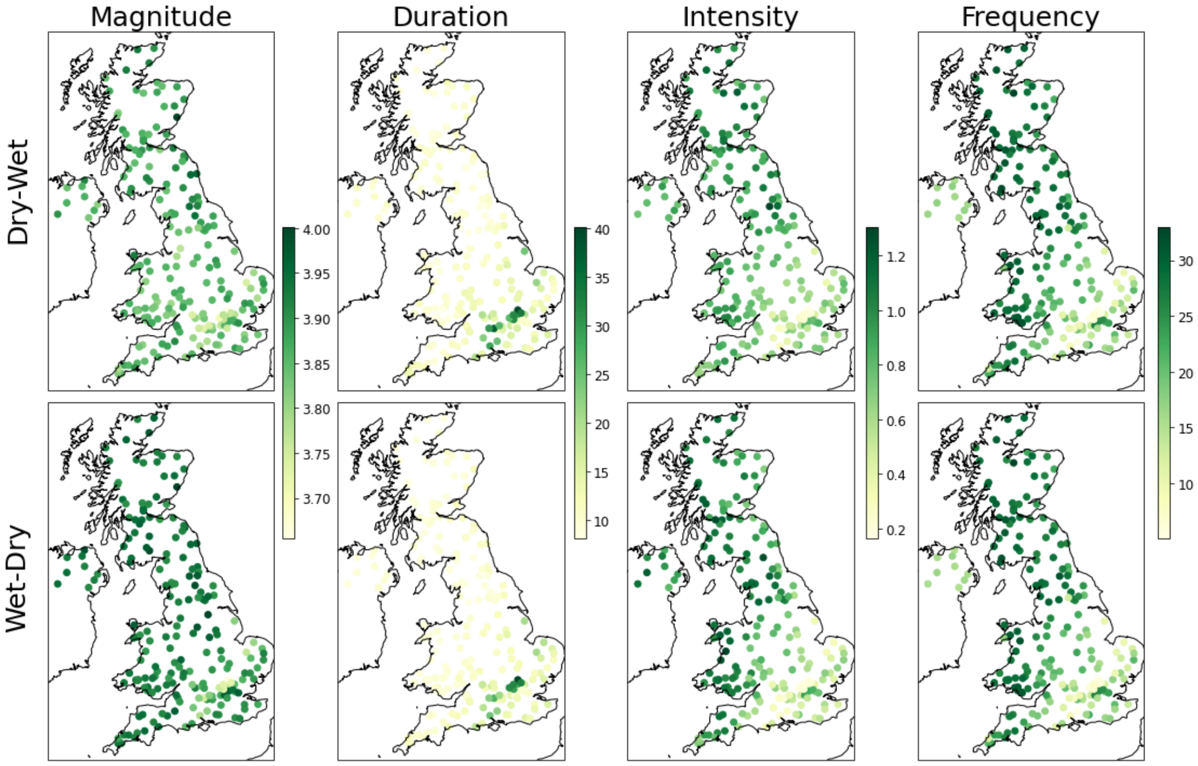

Figure R1 – As for Figure 5 in the original manuscript: Mean magnitude (no units), duration (months), intensity (no units) and frequency (transition events per decade) of severe (threshold ±1.6) dry-wet and wet-dry hydrological transitions in the Baseline period (1989-2018) of SimRCM using SSI1.

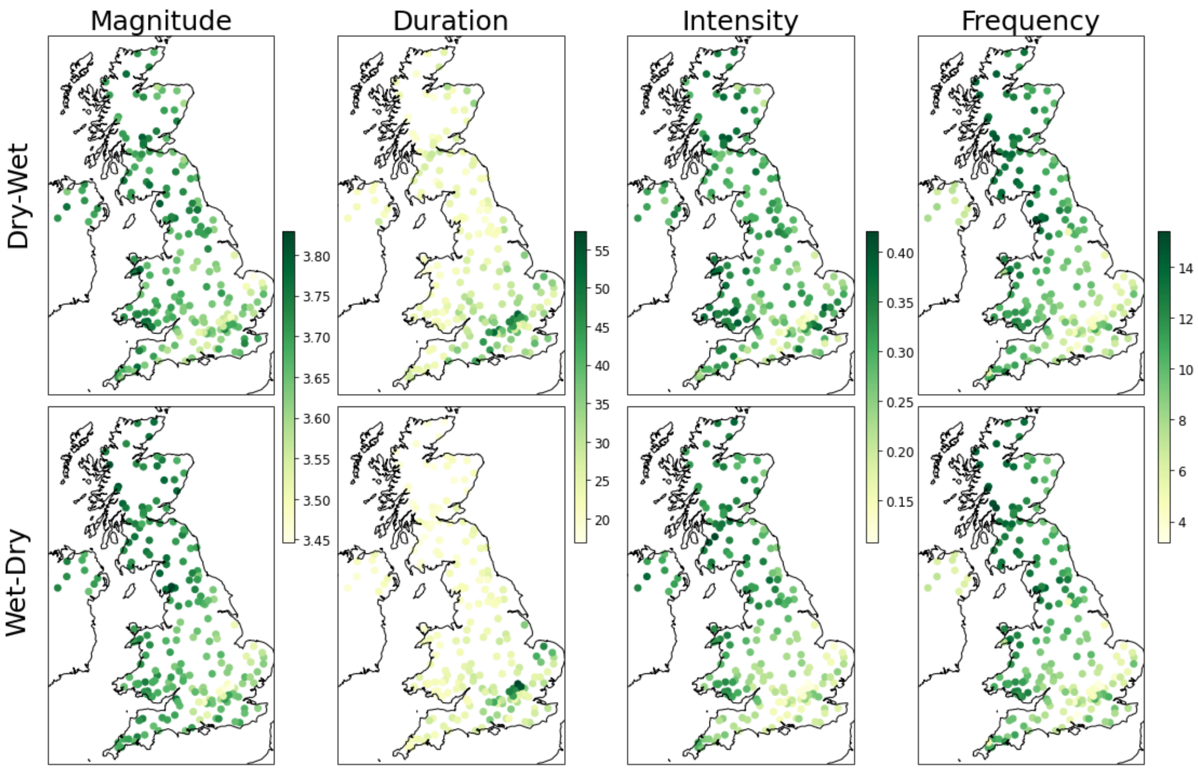

Figure R2 – As for Figure 5 in the original manuscript: Mean magnitude (no units), duration (months), intensity (no units) and frequency (transition events per decade) of severe (threshold ±1.6) dry-wet and wet-dry hydrological transitions in the Baseline period (1989-2018) of SimRCM using SSI6.

- Threshold sensitivity. While the threshold level method has not been applied to the time series specifically, has a sensitivity analysis been undertaken on the different levels/deviations from "normal conditions"? Does this influence the results, and more specifically across both meteorological and hydrological variables? Note that Section 2.3 (L214-216) defines three threshold categories (moderate, severe, extreme), but the figures use ±1.6 only. Either present the other two, the supplement would be an appropriate place or justify ±1.6 directly.

  We chose not to include results using all three thresholds to avoid oversaturating our results with surplus plots. ±1.6 is a threshold used elsewhere in the literature (e.g. Chen and Ford, 2023; Ford et al., 2021) and strikes a balance between the number of events captured (and hence the sample size for analysis) and the severity of the events. In our initial analysis we assessed the sensitivity of transition metrics to threshold used and found the mean transition characteristics and spatial patterns to be broadly similar with the main difference being fewer transitions detected using the higher threshold (see below Figures R3 and R4). We will add to section 2.3 to explain why we choose to focus on the ±1.6 threshold in subsequent results and add the equivalent of Figure 5 to the supplementary material using the ±1 (moderate) and ±2 (extreme) thresholds shown below.

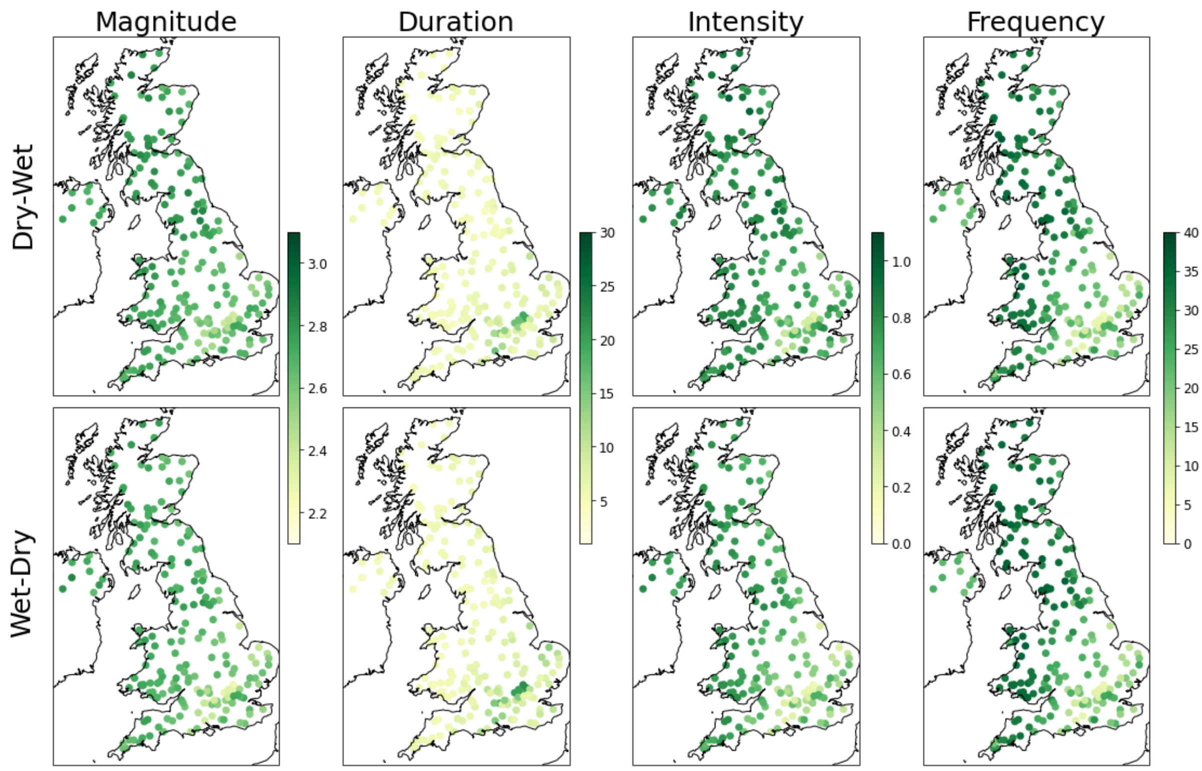

Figure R3 – As for Figure 5 in the original manuscript but with the mean transition metrics calculated for moderate transitions (threshold ±1)

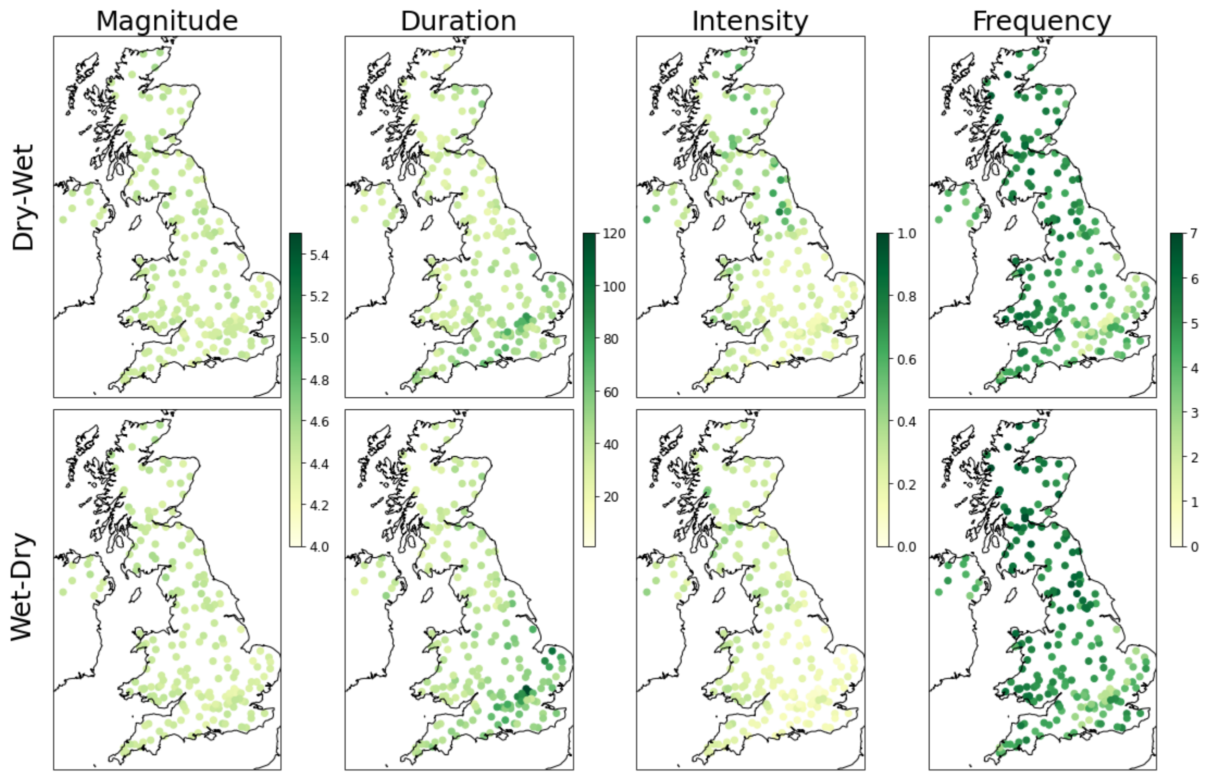

FIgure R4 – As for Figure 5 in the original manuscript but with the mean transition metrics calculated for extreme transitions (threshold ±2)

- Model selection: Why were these specific hydrological models selected? Is it possible to provide a quantitative analysis, or a reference to a paper that quantifies, how well SimObs performs in relation to observations? A citable RMSE or bias statistic would give readers a sense of the scale of the "inherent biases" mentioned at L155-156.

  The four hydrological models were not selected solely for use in our study, we are simply making use of the existing eFLaG projections (Hannaford et al., 2022), which were the latest nationally consistent hydrological projections openly available for the UK at the time the analysis was conducted. The accompanying eFLaG paper (Hannaford et al., 2023) has already quantified the performance of SimObs against observations and so we do not feel it necessary to repeat this analysis here. We will however look to make this less ambiguous in the Data section of the revised manuscript, adding "with median NSE and KGE2 >0.7 for all four models" to L155.

- L202: "Here, we aim to focus on transitions on a broadly seasonal or longer timescale rather than sudden transitions over shorter timescales of days or weeks as these are more relevant to water resource management, where such significant shifts have the greatest impact on water availability planning." While this is valid justification, a more quantitative explanation of "seasonal or longer" timescales would be beneficial. This also bears on the chalk-aquifer interpretation (L257-262): are those long durations genuinely slow, connected transitions, or simply long gaps in catchments where extremes are rare?

  This is a key point to note with our methodology; two extremes separated by a long period of near average conditions will be identified as a transition. In the present paper we do not suggest a maximum duration for a transition event. Without thorough analysis of the drivers of these transition events, and understanding the compounding impacts for each catchment, it is difficult to say that even the shorter duration transitions are truly connected as a compound event and not just consecutive unrelated extreme events. Therefore, without this understanding as yet, we must instead consider whether the impacts of these longer transitions are still of interest, which is why we have chosen not to exclude them from our results and analysis at this stage. We will add this to section 4.1.1 to further expand on the need to understand the drivers and impacts of transitions, in addition to updating line 202 to read "seasonal or interannual timescales".

- Ephemeral and intermittent flows: while transition events are identified as the period between the end of one and the start of another consecutive extreme, have the authors considered aspects such as ephemeral or intermittent flows in the definition of a dry extreme? The Tweedie distribution accommodates zero flows, but the implications for SSI behaviour in intermittent catchments are not discussed.

  This is an interesting point and one we had not yet considered. Intermittence is rare in the eFLaG data (something that was intentional in the catchment selection in the conception of the dataset; Hannaford et al., 2023), with 0 flow days found in only 106 RCM-Model-Catchment combinations (out of a possible ~9500) and the three combinations with the highest percentage of 0 flow days consisting of 9.3%, 5.4% and 2.6% of 0 flow days. The monthly averaging in the calculation of SSI is likely to make any impact of this minor intermittence negligible. We will add this detail to the description of SSI calculation in section 2.2.

- The monthly timescale means this analysis does not capture flashy responses. This could be caveated adequately as it may have implications, particularly for the NW upland catchments where the fastest transitions are reported and where the monthly resolution is most likely to be limiting. Is this something for future research?

  Yes, the catchments in the northwest are flashier and faster responding on shorter timescales, however, the distinction between 'rapid' transitions (e.g. as in Götte and Brunner, 2024) and longer 'state shifts' is important here. Whilst our methodology using monthly timescales will not detect the rapid transitions in the northwest, the area is still susceptible to the longer timescale state shifts between water deficit and surplus, perhaps more so than other slower responding catchments due to the limited storage to buffer impacts of transitions. We already suggest a comparison with 'true' drought and flood transitions (L436-438), but we will add to this to include the implications for different regions of the UK with differing hydrological regimes.

- L126: "for both time slices and transient changes, using multiple hydrological models". Clarity is needed on what time slices and transient changes are analysed.

  We go on to define the time slices used later in the data and methods section, but we will add clarification here too.

- Abstract, L15: "enhanced future Flows and Groundwater (eFLaG) dataset for 1989-2079 over 200 UK catchments", while L135 states "river flow projections across the UK, for 1980-2080". These should be made consistent.

  1980-2080 is the full time period covered in the eFLaG dataset, whilst 1989-2079 is the period of data used in this study which is split into the three time-slices for analysis: Baseline 1989-2018, Near Future 2020-2049, and Far Future 2050-2079, following previous national-scale analyses of the eFLaG dataset (e.g. Parry et al., 2024; Tanguy et al., 2023).

- There is currently no Code Availability statement. The Data Availability section points to eFLaG and the UK Water Resources Portal. Given that the transition identification and characterisation framework is itself a substantive contribution of this paper, this would be beneficial to future research.

Thank you for the comment, we are pleased to hear that the transition identification we have used may be of interest for others, we will add a Code Availability statement to the revised manuscript.

S2: Results and findings

- Is "volatility" the right term? Section 1.1, L49 uses "hydrological volatility" with reference to Swain et al. (2025a) — but that framework is built on SPEI rather than SPI, because evapotranspiration-related variables are increasingly favoured, and Swain et al. show that including PET substantially amplifies projected whiplash increases relative to precipitation alone. Given that evaporative demand is central under RCP8.5 could the Discussion section explain that an SPI/SSI-only approach may understate future changes in transition magnitude and frequency.

  We use volatility as a general term here as it is used elsewhere in the literature (e.g. He et al., 2026; Li et al., 2023). We discuss the effect of evaporation in relation to the differences in our results between hydrological and meteorological transitions (L384-387, Discussion). We use SSI which already integrates precipitation and evapotranspiration to analyse transitions in river flows and so this should account for increased evaporative demand, we will however add to this section to acknowledge that our meteorological transitions, identified using SPI, do not account for evaporation and so future changes may be underestimated.

- Section 1.1, L72: "wet-dry transitions can still be particularly impactful, for example wet-dry transitions across the growing season and wildfire season have been linked to an elevated wildfire risk (Swain et al., 2025b)". This link operates through evaporative demand, humidity and other hydroclimatic variables, not through hydrological variables alone, worth making explicit, as it reinforces the SPEI point above.

  Whilst we acknowledge that the reviewer is correct in that the link between transitions and wildfire risk is not through purely hydrological variables, this point was more intended to illustrate that transitions in both directions (dry-wet and wet-dry) can be impactful and both should be included in transitions studies, as we do here. Therefore, we do not feel it necessary to expand on this point in the introduction.

- Figs. 4 and 8 boxplots are slightly difficult to read. Difference-in-medians panels (NF−BL, FF−BL) alongside the boxplots would draw out the key results effectively.

  We will add to Figure 4 of the original manuscript with the following figure to include difference-in-median panels (example for intensity shown below) to clearly show the differences in average metrics between different hydrological models.

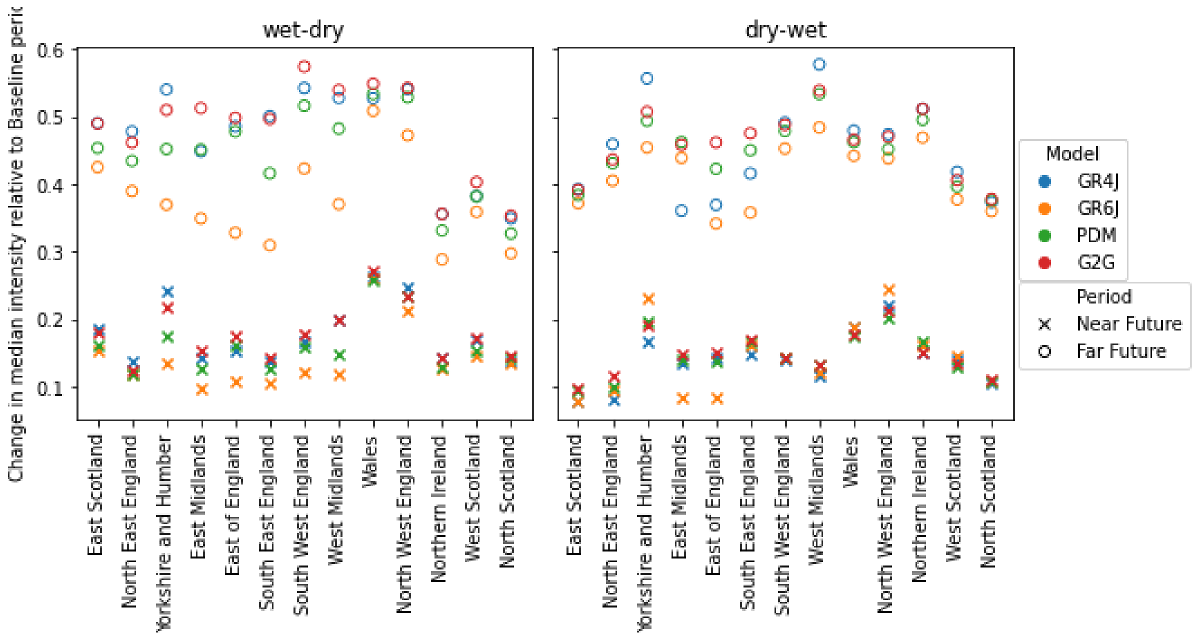

Figure R5 – Difference in median intensity of severe (threshold ±1.6) hydrological (SSI3) transitions relative to the Baseline period for Near Future and Far Future for each of the four hydrological models.

We have had a look at doing similar for Figure 8 but we do not feel this adds any value to the original figure as the main aim of this figure is to show changes in transition metrics across the baseline, near-future and far-future period rather than between hydrological models. The original figure already shows the median (and spread) clearly between the three periods.

- Uncertainty quantification would improve the robustness of the projected transitions. The authors state at L307-310 that internal variability and inter-model uncertainty dominate the projected signal, however explicit quantification of uncertainty may be beneficial in the Results.

We will add text to the manuscript to include quantification of the number of ensemble members showing a projected increase or decrease in transition metrics and will add the below Table R1 to the supplementary material.

Table R1 – The number of RCMs showing an increase in each transition metric from Baseline to Far Future period for Severe (±1.6) wet-dry and dry-wet transitions in SSI3 using the GR6J model.

	Wet-Dry			Dry-Wet		
	Magnitude	Duration	Intensity	Magnitude	Duration	Intensity
East Scotland	12	1	11	12	0	12
North East England	10	1	11	11	1	11
Yorkshire and Humber	11	0	11	12	0	12
East Midlands	11	0	12	9	2	10
East of England	12	0	12	12	2	11
South East England	10	0	12	11	1	11
South West England	11	0	12	12	0	12
West Midlands	10	0	11	11	0	11
Wales	12	0	12	12	0	12
North West England	12	1	11	12	1	12

Northern Ireland	10	1	10	10	1	11
West Scotland	11	1	12	12	1	11
North Scotland	11	1	10	12	0	12

- Area-averaging across UK regions does not show the full catchment-by-catchment spread. How does this affect the interpretability of the results, and what about inter-region heterogeneity?

  The spread of the regional boxplots (e.g. Figure 8 in original manuscript) shows the inter-region heterogeneity and maps (e.g. Figure 5 in original manuscript) show transitions at a catchment level. The present paper sets out to apply nationally consistent river flow projections to characterise transitions across the UK and so a more detailed catchment-by-catchment investigation, whilst interesting, is out of scope here.

- The SimObs/SimRCM comparison is currently visual only (L247-256, Fig. 5). Difference maps (SimRCM − SimObs) for each metric would show immediately where the RCM-driven runs match the observation-driven simulations and where they diverge, and a compact table of regional bias would be beneficial.

  We have looked at plotting the difference between SimRCM and SimObs for each transition metric and whilst we can appreciate why some readers may find it useful to have more of a quantitative comparison between the two, our primary objective in comparing SimRCM and SimObs is to highlight the strong similarity in the spatial patterns of the transition metrics. Thus, the minor differences in the values between SimRCM and SimObs transition metrics (i.e., model bias) is not the main focus point. This is because the 12-member climate ensemble (SimRCM) is not meant to, and will not, replicate SimObs exactly; they include a larger sample of transition events of differing characteristics. These differences between SimRCM and SimObs are already discussed in line 150-152 of the original manuscript: "SimRCM runs do not attempt to replicate actual 'weather' but rather evolve according to the transient response of the RCM – and only replicate the long-term statistics of regimes rather than the day-to-day weather". Figure 5 in the original manuscript shows that transition characteristics (magnitude, duration and intensity) in SimRCM, on average, are comparable in magnitude and very similar in spatial pattern to that in SimObs. Further, we present regional differences in the mean and spread of transition intensity between SimObs and SimRCM using boxplots (Figure 4 in original manuscript), which we feel provides a clearer visual representation of regional biases than a tabulated comparison would.

- The BFI link can easily be made quantitative (L257-262). The mechanistic explanation for the long-duration, low-intensity SE catchments is one of the most interesting findings. BFI is already plotted in Fig. S1, so a scatter of BFI against mean transition duration across all 200 catchments, with a perhaps a correlation coefficient, would improve this finding quantitatively.

Thank you for this suggestion, we will update the revised manuscript to include a scatterplot (Figure R6) showing the correlation between mean duration and BFI across all 200 catchments.

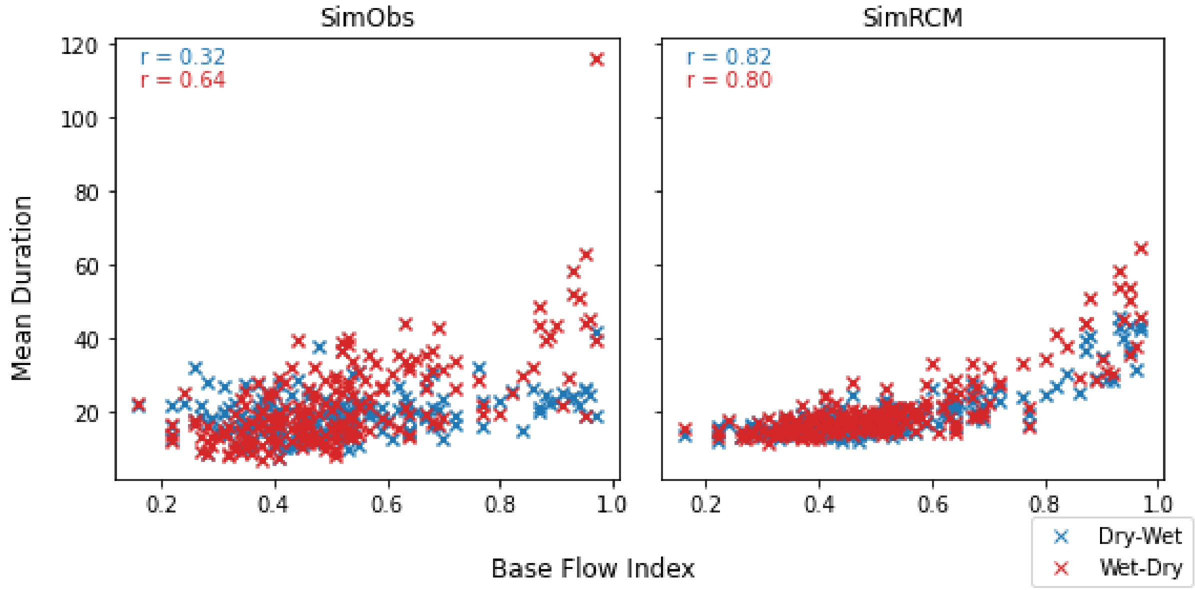

Figure R6 – Scatter plot between baseflow index (BFI, no units) and mean transition duration (months) across all 200 catchments wet-dry (red) and dry-wet (blue) transitions using SimObs (left) and SimRCM (right). Correlation coefficients (r) are given for different transition type within the plots and all shown values are significant at the 0.05 level.

- Modal season may be unstable where transitions are rare (Fig. 7). In low-frequency SE catchments over a 30-year SimObs baseline, the modal season may rest on very few events. Reporting the underlying event counts (marker size) would let readers judge which parts of Fig. 7 are well constrained.

Thank you for this suggestion, we agree this would improve Figure 7, and we will update as below to indicate a count of transition events at each catchment.

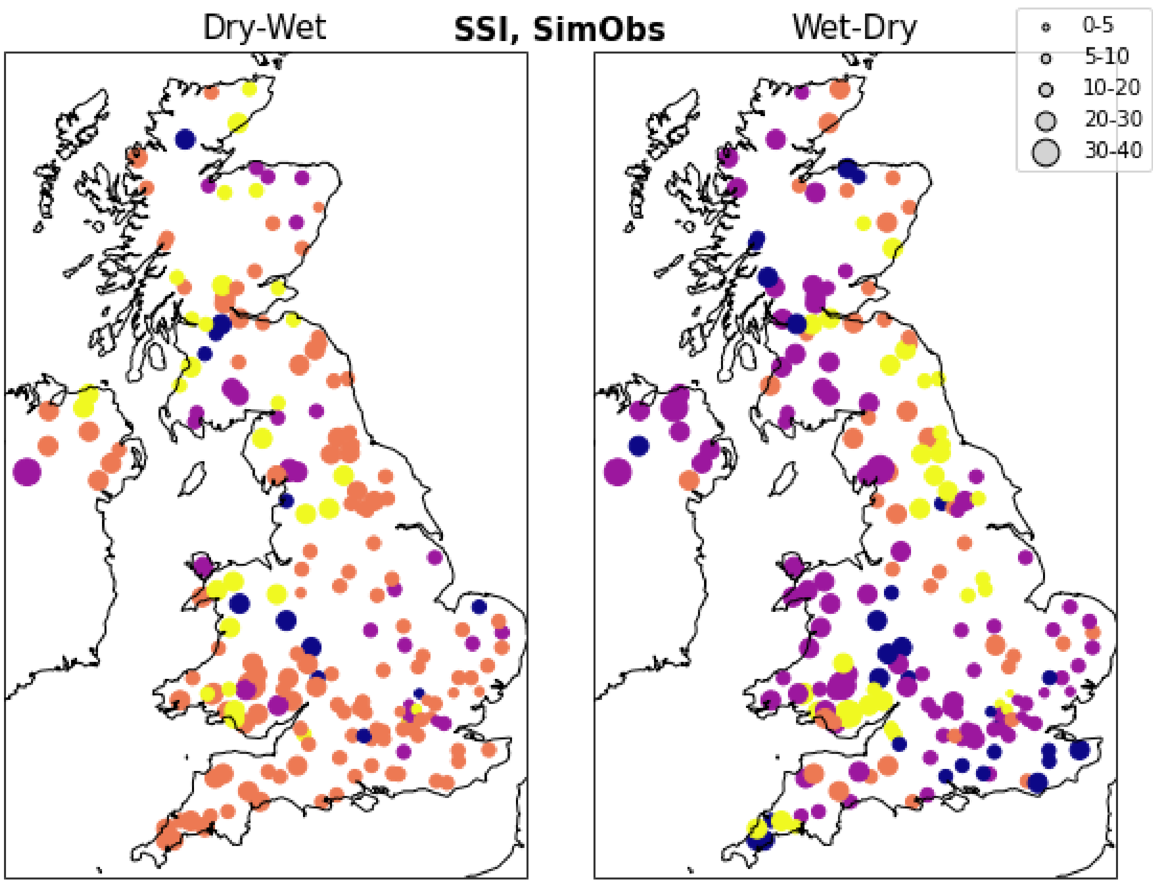

Figure R7 – as for Figure 7 in the original manuscript: Modal season of transition occurrence of severe (threshold ±1.6) hydrological (SSI) transitions in the baseline period (1989-2018) with marker size representing the underlying event counts.

- The state-switch vs. rapid-transition distinction could appear earlier in the paper. This is currently confined to Sect. 4.1 (L425-438), but may be useful in the Introduction to compare this work with Götte and Brunner (2024), Matanó et al. (2024) and Hammond et al. (2025). The smoothing inherent in SSI-3, limit detection of rapid, asymmetric behaviour that event-based methods capture. This is an interesting methodological finding in its own right and could be presented as such.

  We agree that this is an important clarification that could be introduced earlier in the paper, especially when discussing literature that may use different definitions of transitions. We will add the distinction between seasonal/'state switch' and 'true'/rapid transitions to our introduction.

  Event-based methods often detect fewer flood to drought transitions – due to the typically slow developing nature of a drought – leading to the asymmetry, whereas our methodology allows us to detect transitions in both directions. We are pleased that the reviewer thinks this is a finding of interest, and will add this point to our discussion.

S3: Title suitability

- The title accurately reflects the hydrological analysis, but does not mention meteorological transitions. This is clear from the abstract itself, L18: "both river flow and precipitation to understand the magnitude, duration and frequency of both hydrological and meteorological transitions". I would suggest amending the title to address both, for example "Historical and future transitions between opposing hydrological and meteorological extremes in the UK" or similar.

Thank you for raising this point, we agree that the meteorological transitions contribute equally to our results with the hydrological transitions and so will update the title to reflect this.

Technical corrections

- L47/48: full stop needed after (IPCC, 2023).

  Will add in the revised manuscript.

- L81: spelling correction to "Millennium".

  Will correct in the revised manuscript.

- L431: "methods that capture much more rapid changes transitions", suggest removing the word changes.

  This looks like a tracked change that slipped through, we will correct in the revised manuscript, thank you.

- L448: "Chan et al., 2025" — 2025a or 2025b?

  This refers to the paper Chan et al., 2025a, we will update references in the revised manuscript accordingly.

- Abstract, L16: study period given as 1989–2079, while Sect. 2.1 gives 1980–2080 for the data.

  1980-2080 is the full time period covered in the eFLaG dataset, whilst 1989-2079 is the period of data used in this study which is split into the three time-slices for analysis: Baseline 1989-2018, Near Future 2020-2049, and Far Future 2050-2079, following previous national-scale analyses of the eFLaG dataset (e.g. Parry et al., 2024; Tanguy et al., 2023).

- Figs. 8 and S4: rotated region labels are very small and hard to read at print size, abbreviations or larger figures/text might help.

  We will abbreviate and increase the text size of the region labels.

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