



# Historical and future transitions between opposing UK hydrological extremes

Rachael Armitage<sup>1</sup>, Eugene Magee<sup>2</sup>, Amulya Chevuturi<sup>1</sup>, Wilson Chan<sup>1</sup>, Jamie Hannaford<sup>1,3</sup>

<sup>1</sup>UK Centre for Ecology & Hydrology, Benson Lane, Crowmarsh Gifford, Wallingford, OX10 8BB, UK

5 <sup>2</sup>UK Centre for Ecology & Hydrology, Library Avenue, Bailrigg, Lancaster, LA1 4AP, UK

<sup>3</sup>Irish Climate Analysis and Research UnitS (ICARUS), Maynooth University, Maynooth, Ireland

*Correspondence to:* Rachael Armitage (racarm@ceh.ac.uk)

## Abstract

Transitions between droughts and floods can exacerbate the impacts of the individual events and present a complex challenge  
10 for water resource management: sudden or frequent transitions between dry and wet conditions can negatively impact water  
availability, water quality, agricultural productivity, and cause damage to water infrastructure. Despite these potentially severe  
impacts, such transitions have, until recently, received less attention in the international literature than their component  
extremes. In the UK, there has been no systematic assessment of the occurrence of transitions, despite growing interest given  
a series of recent swings between floods and droughts.

15 Given this gap, we assess present-day and future transitions using national river flow and precipitation projections from the  
enhanced future Flows and Groundwater (eFLaG) dataset for 1989-2079 over 200 UK catchments. We identify transition  
events as the period between consecutive yet opposite extremes at seasonal timescales, using a threshold method to demarcate  
extreme wet and dry events for both river flow and precipitation to understand the magnitude, duration and frequency of both  
hydrological and meteorological transitions.

20 Our results reveal the spatial distribution of transitions in the UK, with higher intensity transitions in the north-west and longest  
durations in the south-east. We compare hydrological and meteorological transitions and find similar spatial patterns between  
the two but a stronger seasonality and generally shorter durations for meteorological transitions. Most regions of the UK are  
projected to see an increase in transition magnitude, a decrease in duration and therefore more intense transitions in the future.  
The south-east sees the largest decreases in transition duration under future projections. The frequency of hydrological  
25 transitions is projected to increase in the north-west and in all regions for meteorological transitions. Our findings demonstrate  
the risk of increasing hydrological volatility across the UK, with implications for water resources management and climate  
adaptation.

## 1. Introduction

Although droughts and floods exist at opposite ends of the hydrological regime, their consecutive occurrence can significantly  
30 impact water resource management (Brunner, 2023), highlighting the need to understand and anticipate these complex events.



Transition events – temporally compounding events consisting of a switch from one extreme to the other – are becoming a rapidly widening area of research within the hydrological research community (Barendrecht et al., 2024). Transitions have been presented under a variety of pseudonyms in the existing literature, with differing definitions and event identification approaches employed over a range of timescales. Examples include hydrological whiplash (Hammond et al., 2025),  
35 hydroclimate volatility (Swain et al., 2025a) and drought-to-flood events (Matanó et al., 2022, 2024), among others. Alongside the growing research interest in transitions, there is also a growing media attention to such events – largely picked up by buzzwords such as ‘whiplash’.

Many communities are susceptible to both droughts and floods. When these events follow in relatively quick succession (i.e. a transition event) impacts of the individual component events can be exacerbated, in part due to communities and  
40 infrastructure not having time to recover from the first extreme event before the opposite extreme event follows (Brunner et al., 2021b; Kreibich et al., 2022). Moreover, transitions between droughts and floods can negatively impact water quality, agricultural productivity, and water management infrastructure, among others, especially if water resources managers are taken by surprise by sudden transitions from one extreme to another (van Vliet et al., 2023), with wider implications for public health, food and water security, and infrastructure (Jaroszweski et al., 2021). It is therefore important to consider not just  
45 droughts and floods in isolation but also the transitions between droughts and floods and vice versa.

### 1.1. Hydrological Wet-Dry and Dry-Wet transitions

In many areas of the world, the frequency, intensity and severity of droughts and floods are increasing, and are expected to continue to do so with further climate change (IPCC, 2023) However, it is unclear whether the persistence of wet and dry periods is increasing or whether an overall increase in hydrological volatility - with frequent and rapid switches between floods  
50 and droughts, is to be expected (Swain et al., 2025a).

Increasing hydrological variability poses challenges for water resources management, with current policy and practices designed for only a given range of variability. Many risk reduction measures in place for one hydrological extreme can be unintentionally detrimental in the management of the opposite extreme (Kreibich et al., 2022; Ward et al., 2020). For example, discharging water during a flood due to expected further flooding may exacerbate water scarcity during a subsequent drought.  
55 Management measures may be rendered less effective at mitigating the hazard they were designed for when impacted by the opposite extreme – such as increased erosion due to flooding causing sedimentation in reservoirs and reducing storage capacities – as summarised by Ward et al. (2020). If suitably severe, flood and drought events typically require some level of emergency response that requires mobilisation, requiring the relevant authorities to swiftly reorganise and reallocate funding; if the opposing extreme were to happen subsequently, this can make it very challenging to re-prioritise and marshal suitable  
60 resources (Leonard et al., 2014). Transitions also change the reaction time required from decision makers (Hammond et al., 2025; Muñoz-Castro et al., 2026). Thus, transitions demonstrate a particular challenge for water resource management and require significant changes in traditional water management practices, yet, currently, there exist fewer studies on such transition events in comparison to research directed at the component extremes in isolation.



65 Studies into hydrological transitions, along with a lot of the attention in the news media and wider society, have largely focused  
solely on drought to flood transitions (e.g. Matanó et al. 2024; He and Sheffield 2020). Transitions from flood to drought are  
rarely considered in hydrological transition studies, mostly due to the assumption that following a flood, sufficient water would  
remain stored to buffer the impacts of a subsequent drought. However, this is not often the case, especially for areas with  
limited storage capacity, as illustrated by the transition from flooding in November 2009 (Miller et al., 2013) to the fast-  
developing drought in spring 2010 in northwestern UK (Kendon et al., 2013). Furthermore, flood impacts are usually apparent  
70 during or immediately after the event, whereas drought impacts can have a much slower and less well-defined onset and so,  
whilst there may be a sudden switch in state from wet to dry, the impacts may not follow immediately resulting in such events  
not registering in the collective consciousness as transitions. However, 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). In addition to challenges in preparedness and redistribution of resources at short notice, wet-dry  
75 transitions (alongside volatility more generally) can also lead to problems in communication between water managers and  
water users. A perceived lack of water availability soon after flooding can present difficulties in risk communication with  
potential mistrust and a lack of uptake of management measures under traditional communication narratives and instead  
requires consideration of how best to meaningfully communicate alternating drought and flood risk during transitions (Shaw  
and Corner, 2016).

80 Although transitions are an emerging focus in hydrological research, there have been many severe and impactful transition  
events documented globally. The Millenium Drought in Australia (2000-2010; e.g. Van Dijk et al., 2013) was quickly followed  
by widespread flooding in southern and eastern Australia in 2010 (Barendrecht et al., 2024), with socio-economic and  
environmental impacts (MacMahon et al., 2015). Other examples include the 2022 floods in Pakistan which, following a  
drought period, caused displacement and loss of life (FloodList, 2025; Khan et al., 2022); and the 2021 flooding in Chile  
85 during the dry season which impacted agriculture and infrastructure (Valenzuela et al., 2022).

## 1.2. Transitions in the UK

In recent years, the UK has experienced a number of extreme flood events and drought events that have been closely  
interspersed, mirroring an increase in hydroclimatic volatility in line with global findings (Swain et al., 2025a). Just within the  
last decade, alternating UK drought and flood events include the 2015/2016 floods (Barker et al., 2016a), 2018 drought (Turner  
90 et al., 2021), 2019-2021 floods (Griffin et al., 2025), 2022 drought (Barker et al., 2024), 2023/24 floods (Chan et al., 2025b),  
followed by most recently the 2025 drought (Carbon Brief, 2026). This recent hydrological volatility, and the expected  
increased variability of the future UK climate, highlights the need to understand and better prepare for transitions. Many  
transitions are associated with anomalies to the usual seasonal pattern and so seasonal river flow and climate trends towards  
wetter winters and drier springs in the UK (Hannaford et al., 2025) may further encourage the occurrence of transitions.

95 Historical examples of transitions in the UK include the 1976 drought – widely considered one of the most impactful and  
severe droughts in the historical observations (Rodda and Marsh, 2011) – which was abruptly terminated in the autumn of



1976 by months of high rainfall (Parry et al., 2013). The most notable example in recent years is the 2010-2012 drought (Kendon et al., 2013) which was preceded by flooding in the northwest (Miller et al., 2013) and ended with further widespread flooding and the wettest April-July period for England and Wales in nearly 250 years (Parry et al., 2013). Impacts were widespread and affected many sectors: reduced agricultural yields, crop losses and contamination of agricultural land; damage and disruption to road and rail infrastructure; destruction of ecological habitats (Parry et al., 2013). Many of the reported impacts were related to flooding, although these could have been exacerbated by the preceding drought. However, Parry et al. (2013) also suggested that the dry period before the floods could moderate flood impacts, and that the succeeding wet period helped alleviate water resource concerns – a potential benefit that is not always considered in the framing of transitions. While the end of the drought has been well studied, the 2010-2012 drought was, in effect, bracketed by transitions, with the onset being a notable example of a wet-dry transition. In northwest England, November 2009 saw catastrophic flooding (Miller et al., 2013) but following an exceptionally dry start to the year, concern rapidly switched to drought as reservoir levels plummeted in the same region, leading to water use restrictions in the early summer (Parry et al., 2013).

Despite these historical examples, there have been very few previous studies investigating transitions events in the UK. Motivated by the extreme 2010-2012 transition, Parry et al. (2016a) assessed drought termination in the UK, primarily focusing on the end of a drought (i.e. recovery from drought to “normal” conditions) rather than the temporally compounding extremes of transitions. That is, Parry et al.’s definition considers only part of a transition event, but does not go as far as considering any subsequent excess that may be associated with flooding. Parry et al. (2016b) noted how some historical droughts do in fact end with flooding (as in the totemic 2010-2012 case) but many end far less dramatically with a slow return to normal conditions. The work of Parry et al., (2016a, b) is also focused on historical occurrence of drought recovery, but until recently there have been no assessments of whether transitions in the UK may become more severe under climate change. While recent volatility has certainly led to much speculation of changing transitions, there remains a need to quantify how extremes may evolve under anthropogenic warming. While the UK has a rich literature investigating future projections of floods or droughts, a great majority focus on one or other extreme separately, using very different event definitions and metrics (e.g. comparing projections of future hydrological drought (e.g. Parry et al., 2024) and floods (e.g. Griffin et al., 2024) based on the latest national climate projections). Some studies have assessed future floods and droughts together (e.g. Collet et al., 2018; Lane and Kay, 2021) to identify ‘hydro-hazards hot-spots’ but these studies have not addressed transitions between the two extremes.

### 1.3. Aims and Objectives

We aim to fill these current gaps by carrying out the first comprehensive analysis of present-day and potential future changes in the characteristics (magnitude, duration, intensity, and frequency) of seasonal or longer hydrological and meteorological transitions in the UK over the 21<sup>st</sup> Century, for both time slices and transient changes, using multiple hydrological models. Our key objectives are to: i) quantify historical meteorological and hydrological transitions using observation-driven multi-model hydrological simulations, ii) investigate potential future changes in the magnitude, frequency, duration and intensity of



transitions and iii) compare the characteristics, spatial distribution and future changes between meteorological and hydrological  
130 transitions.

## 2. Data and Methods

### 2.1. Data

Figure 1 summarises the data and methods used in this study. We identify and analyse transition events using the Enhanced  
Future Flows and Groundwater (eFLaG) dataset (Hannaford et al., 2022, 2023), which provides a set of nationally consistent  
135 river flow projections across the UK, for 1980-2080, based on the latest national climate change projections for the UK  
(UKCP18; Lowe et al., 2018). The UKCP18 regional projections underpinning the eFLaG river flow projections consists of a  
perturbed parameter ensemble of 12 regional climate model simulations at 12km resolution following the RCP8.5 emission  
scenario, representing the upper range of projected global emissions scenarios (Lowe et al., 2018). We use the UKCP18  
catchment average rainfall and simulated river flows driven by UKCP18 (abbreviated as SimRCM) for 200 catchments in the  
140 UK (Figure 2), from four hydrological models: Grid-to-Grid (G2G; Bell et al., 2007), Génie Rural à 4 paramètres Journalier  
(GR4J; Perrin et al., 2003), Génie Rural à 6 paramètres Journalier (GR6J; Pushpalatha et al., 2011) and Probability Distributed  
Model (PDM; Moore, 2007). G2G is a national gridded hydrological model at 1km resolution while the others are lumped  
catchment hydrological models. Note that the G2G model does not include Northern Ireland and five other catchments where  
no suitable outlet could be located on the 1km river network, and so only includes 186 catchments in Great Britain. Further  
145 details of the climate data pre-processing, including bias correction procedure and hydrological modelling can be found in  
Hannaford et al. (2023).

There are two sets of model outputs in eFLaG – a SimObs run (i.e. observation-driven simulation) and SimRCM runs (i.e.  
driven by the Regional Climate Model simulations). In this study we use both, for different purposes. The SimObs runs were  
generated by driving the four hydrological models with observed data from the HadUK-Grid meteorological dataset (Hollis et  
150 al., 2019). This provides a proxy for observed historical river flow data. The 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. Hence, SimObs allows us to look more realistically at transitions in detail in the  
present-day instead of actual river flows observations, as this allows consistency between the current and future periods (i.e.  
we are comparing hydrological model runs with each other). Previous assessments have already demonstrated that the SimObs  
155 runs generally perform well against observations, although inevitably there are inherent biases which would limit the value of  
comparing historical observed transitions with future model-based assessments (Hannaford et al., 2023).

In comparison, SimRCM data (i.e. simulated river flows driven by the UKCP18 Regional Climate Model projections) are  
available for the full 1980-2080 period for 12 ensemble members. Simulated river flows from eFLaG are assessed over three  
time-slices: Baseline (BL; 1989–2018), Near Future (NF; 2020–2049), and Far Future (FF; 2050–2079). The baseline time  
160 slice in SimRCM is used for comparison with future changes within each RCM run. We also appraise the ability of the RCM



to capture observed transitions by comparing the baseline period in both SimObs and SimRCM, to provide added confidence in our future RCM projections.

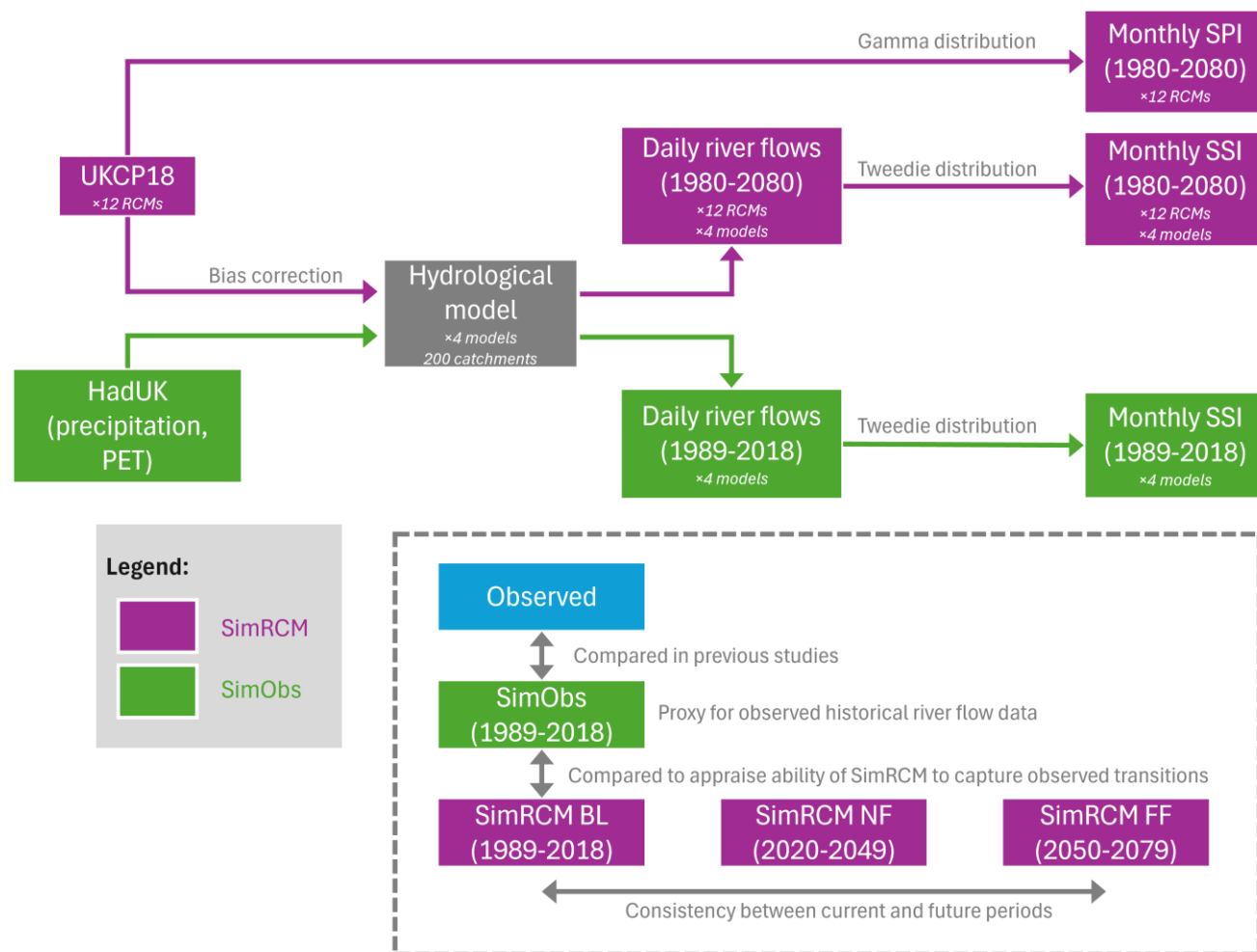
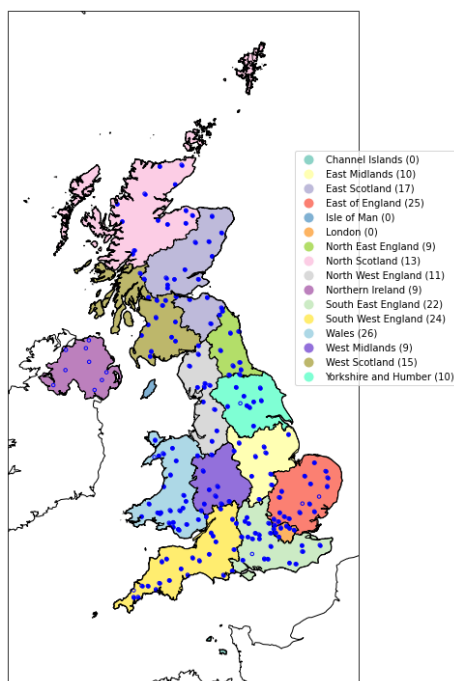


Figure 1 – Schematic summarising the data used in this study. The upper flow chart shows the data and processing used. The schematic in the dashed box illustrates the use of each model output, as discussed in Section 2.1.

165



**Figure 2 – eFLaG stations (round markers) and administrative regions of the UK used in UKCP18 (shaded regions). Stations not included in G2G are shown with hollow markers. The number in brackets indicates the number of stations within the region.**

## 2.2. Standardised Indices

170 Simulated river flows from the four hydrological models were used to calculate Standardised Streamflow Index (SSI) for each  
catchment, following the methodology in Svensson et al. (2017). SSI is a widely used indicator in drought monitoring,  
facilitating the analysis of river flows in comparison to typical conditions for the time of year (Barker et al., 2022). SSI was  
calculated by fitting a Tweedie distribution to monthly mean of the daily simulated river flows, concluded to be the most  
appropriate probability distribution for calculating SSI for UK catchments (Svensson et al., 2017). SSI over the historical  
175 period was calculated using simulated observed (SimObs) river flows over the 1982-2018 period. The same period was used  
to calibrate SSI distribution parameters from simulated river flows from each of the 12 UKCP18 ensemble member (i.e.  
SimRCM). The calibrated Tweedie distribution parameters for each ensemble member are then used to calculate SSI for the  
entire 1982-2080 period, creating internally consistent time series of SSI for each ensemble member and each hydrological  
model. By extending our methodology to include calculating SSI, we reduce model differences in comparison to transitions  
180 identified from raw modelled flows.

The Standardised Precipitation Index (SPI; Mckee et al., 1993) was calculated for the same catchments for comparison between  
hydrological and meteorological transitions. SPI was calculated in the same manner as SSI but rainfall over the 1982-2018  
period was fitted with the standard gamma distribution instead. SPI was calculated using simulated rainfall from the 12



ensemble members in UKCP18 (corresponding to SSI SimRCM). For both SPI and SSI, we use the 3-month accumulation  
185 period (SPI-3 and SSI-3) to focus on meteorological and hydrological transitions at a seasonal time scale.

The use of standardised indicators allows for a simple single threshold approach for extracting extreme events from a given  
time series. The ability of standardised indicators to capture long-term anomalies from the mean was also a key consideration,  
as this enables analysis of extremes and transitions on timescales relevant to water resource management. A further advantage  
of the methods used is that the same thresholds for extracting transitions are applied for all catchments without the need to  
190 vary thresholds and criteria per catchment or index. This aids comparison across catchments and between meteorological (SPI)  
and hydrological (SSI) transitions.

### 2.3. Defining and characterising transition events

Whilst temporally compounding events have been studied extensively following the framework in Zscheischler et al. (2020),  
much of the previous work has largely focused on transitions in meteorological extremes, such as rapid swings in temperature  
195 (e.g. DeGaetano & Lim, 2020) or precipitation (e.g. Chen & Ford, 2023; Ford et al., 2021). One challenge of choosing to take  
a more hydrological view is the many ways in which droughts and floods, and consequently, transitions between the two, can  
be defined.

Transitions between hydrological extreme events can be defined in different ways, with the selected method affecting the  
number, timing and characteristics of identified transition events (Anderson et al., 2025), as for the extreme events themselves  
200 (Coles and Eslamian, 2017; Eslamian and Eslamian, 2022). The wide array of technical definitions can make it difficult to  
compare across approaches, but no single approach is definitive, and the method used should be selected to ensure that the  
transition events captured are meaningful to the sector(s) of interest. 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. Given our focus  
205 on seasonal transitions, we are looking strictly at transitions between periods of wetter (higher flows) and drier (lower flows)  
than normal conditions, rather than between individual drought and flood events per se – although of course the periods of  
wet/high or dry/low flows often correspond to major flood or drought events.

In this study, we define a transition event as the period between two consecutive but opposite extremes (Figure 3). These wet  
and dry extremes are identified on a monthly timescale by applying a threshold method to a time series of SPI/SSI (Section  
210 2.2). If an extreme event is followed by another of the same type, the first extreme event is not considered. We consider only  
the last extreme event before an extreme of the opposite sign (Figure 3). For example, if two consecutive dry seasons are  
followed by a wet event, only the last pair of events is taken as a transition. This method effectively means that we consider  
the transition event to be from the ‘end’ of one extreme (or period) to the ‘start’ of the subsequent opposite extreme.

Three SPI/SSI thresholds are used to identify extreme events, giving rise to three different categories of transition event:  
215 moderate (-1 and +1), severe (-1.6 and +1.6), and extreme (-2 and +2), corresponding to confidence intervals of ~68%, ~90%,  
and ~95% respectively. In all cases, the negative threshold is used to identify dry events and the positive threshold for wet

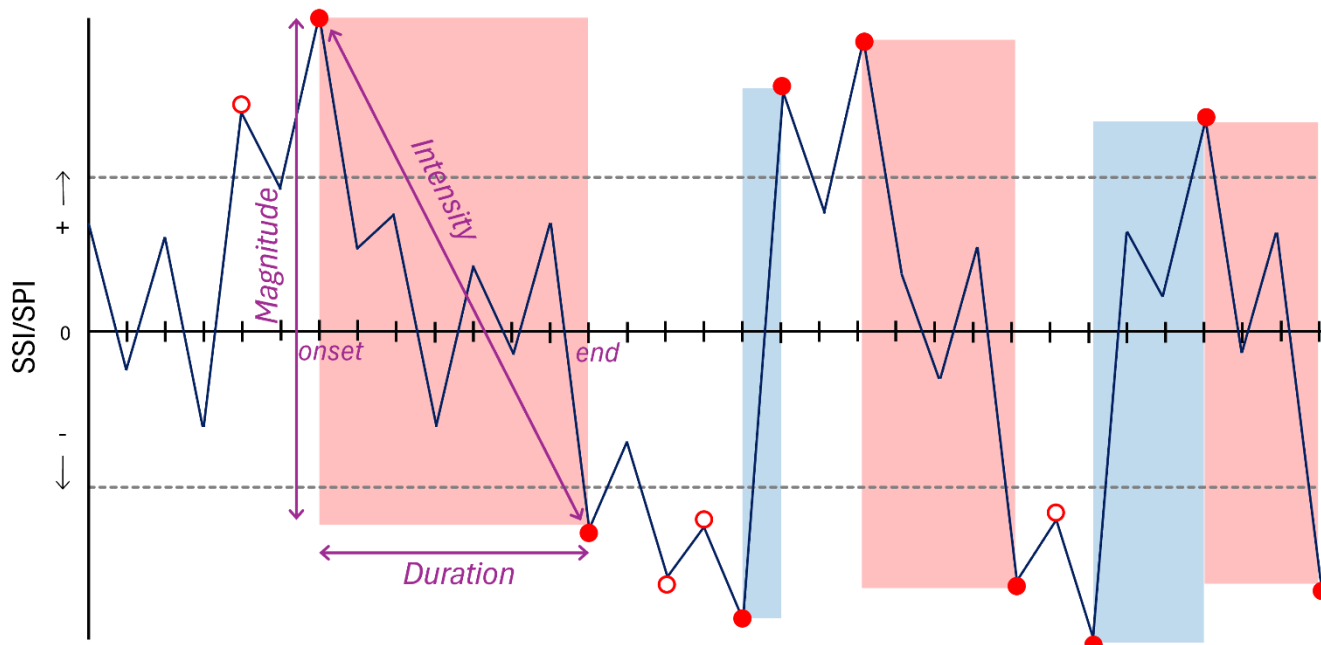


events. The selected thresholds are applied consistently across the future periods (BL, NF, FF), meaning we can compare the transitions identified across periods, rather than using time-varying thresholds based on the conditions of each period (Tanguy et al., 2023).

220 We define four key transition metrics to aid in the characterisation of transitions: duration, magnitude, intensity, and frequency (Figure 3). Duration, the length of the transition event, is defined as the time between the onset and end of the transition event in months, with onset being the month that exceeds one threshold and end being the next month that crosses the opposite threshold. Magnitude is here taken as the difference in SSI (or SPI) value between the two opposite extremes making up the transition event. Intensity is calculated as the magnitude of the event divided by its duration (i.e. the gradient of change between the two opposite extreme events). Intensity is calculated as the magnitude of the event divided by its duration (i.e. the gradient of change between the two opposite extreme events).

225 the two opposite extreme events). Frequency is expressed as number of transitions per decade, a timeframe selected to provide interpretable and meaningful values.

To assess the seasonality of transitions, we calculate the modal calendar month of transition occurrence based on the end month of each event to include the period when impacts are felt the most, following a similar approach to Götte and Brunner (2024).



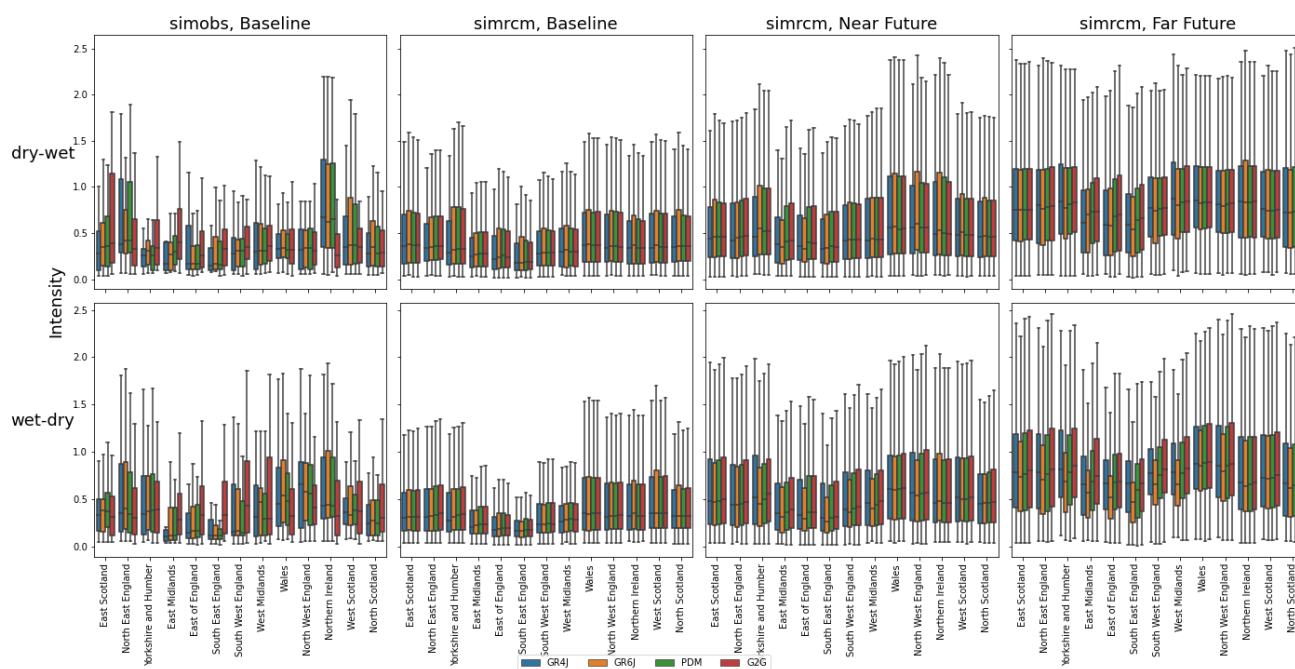
230 **Figure 3 – Schematic demonstrating the identification of extreme events and transitions. Extreme events over the given threshold (dashed grey line) comprising a transition are denoted by solid red markers, whilst extreme events discounted from transition identification are shown by hollow red markers. Shaded red periods represent a wet-dry transition and shaded blue periods a dry-wet transition.**

### 3. Results

235 We present our results in two parts – firstly, characterising historical transitions in the UK, followed by projected changes in these transitions and their associated characteristics.



We first quantify the differences in transition metrics across the four hydrological models. Figure 4 shows mean regional transition intensity (accounting for both magnitude and duration) for each time slice across the four models for SimRCM and SimObs, and wet-dry and dry-wet transitions. Differences between hydrological models, particularly in the SimRCM transitions are not notably large, with the exception of the G2G model which shows a larger spread in the SimObs transitions in some southern and southwestern regions of the UK, and more so for wet-dry transitions.



**Figure 4 – Boxplot representing region-averaged intensity (no units) of severe (threshold  $\pm 1.6$ ) hydrological (SSI) transitions for each hydrological model (GR4J, GR6J, PDM, G2G).**

### 3.1. Characterising historical transitions

Historical transitions are assessed using observation-based data over the baseline (BL) period (SimObs; 1989-2018). Although they are subject to hydrological model uncertainty, consistency with future projections is maintained. We also compare hydrological transitions in the SimObs data against SimRCM data over the same period to evaluate the suitability of the ensemble projections in representing historical transitions. Past studies have confirmed the UKCP18 projections to be suitable for reproducing rainfall patterns in the UK (e.g. Tanguy et al., 2023) and so comparisons between meteorological transitions in the SimRCM data and observed rainfall are not shown here.

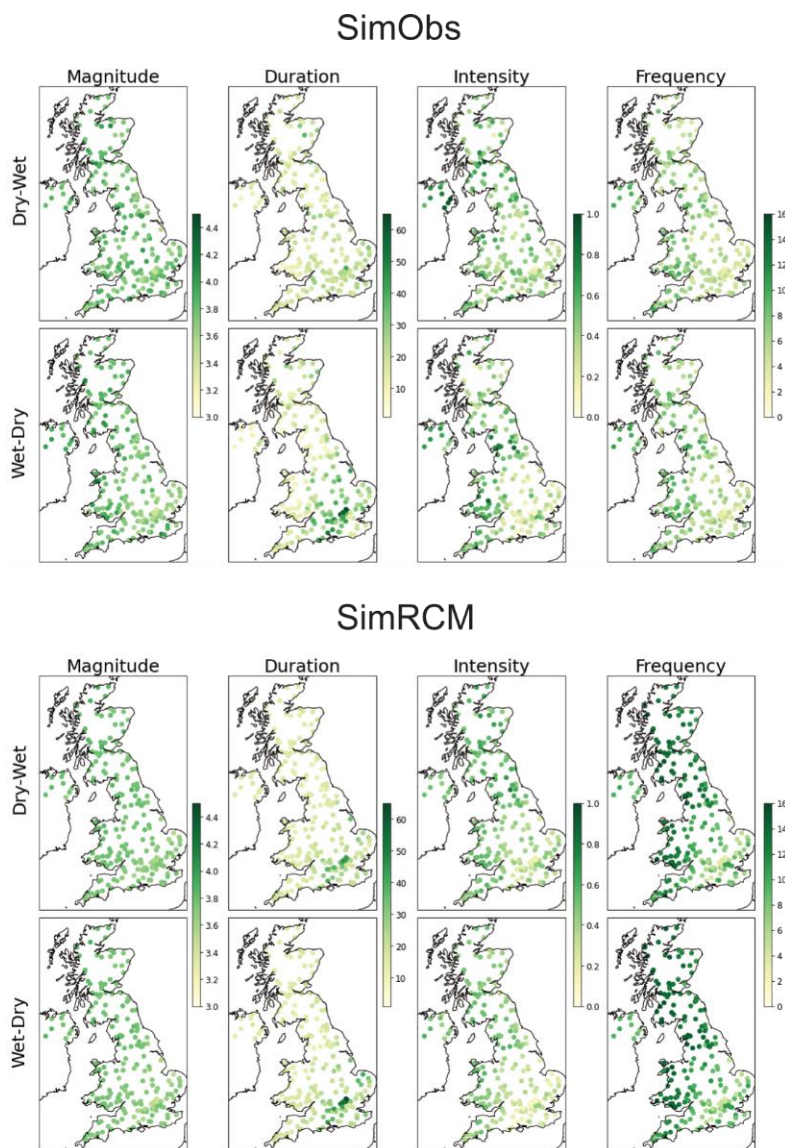
For each transition metric (magnitude, duration, intensity and frequency) we find a similar spatial pattern, with a northwest-southeast gradient in hydrological (SSI) transitions using SimObs (Figure 5). Transitions in the northwest generally have a shorter duration, and therefore a higher intensity, than those in the southeast where some catchments show a mean transition duration of 30 months or longer. There is also a higher frequency of transitions in the northwest. These patterns are well-captured in the SimRCM transitions (Figure 5). This northwest-southeast divide is a common pattern in UK hydrology, as



260 many catchments in the southeast are groundwater dominated and slower to respond (hence longer duration, lower intensity and frequency of transitions), whilst catchments in the northwest are flashier (Figure S1). A few catchments in the southeast show notably high duration and low intensity transitions (Figure 5). These stand-out catchments, situated in the chalk aquifer north of London, are heavily influenced by groundwater levels and do not respond as quickly to meteorological extremes as other catchments which may contribute to longer transition events. However, our results also show the same NW/SE split in meteorological transitions (Figure 6) which are not influenced by the underlying geology.

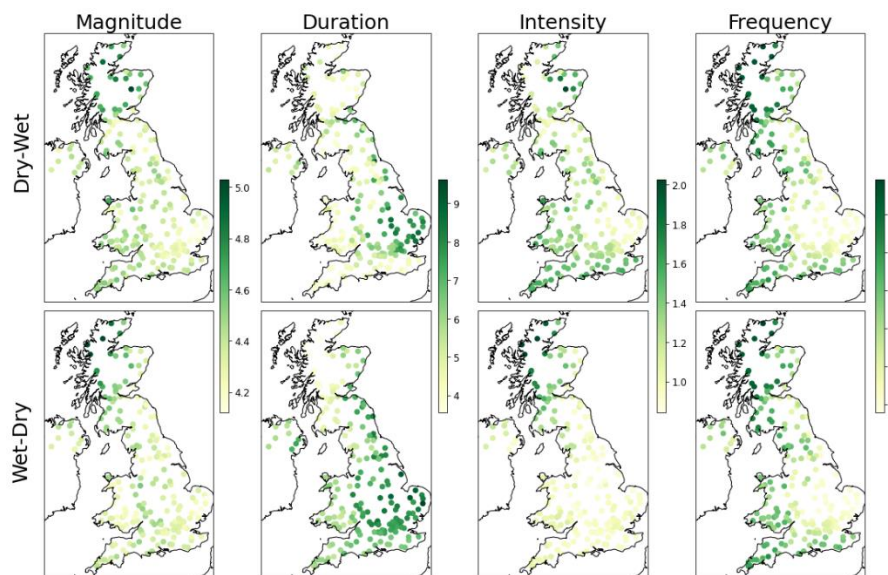
265 Meteorological transitions reflect the spatial gradient of average annual rainfall in the UK. Typically, the northwest is wetter than the southeast, with some catchments in western Scotland receiving in excess of three times the rainfall experienced in southeastern England (Figure S1). Consequently, the longest duration meteorological and hydrological transitions are found in southeast England, given its relative proneness to longer periods of dryness and fewer extreme wet periods (and hence an overall lower frequency of transition events in these catchments). At all catchments, the mean duration of meteorological transitions (Figure 6) is notably shorter than that of hydrological transitions (Figure 5).

270 We see broadly the same spatial patterns in both dry-wet and wet-dry transitions for each transition metric (Figure 5), with the exception being duration and intensity (i.e. in the southeast where wet-dry transitions show notably longer durations – and therefore lower intensities than for dry-wet transitions). The large range of transition durations across the selected catchments confirm it is appropriate to focus on seasonal scale and longer transitions for the UK.



275

Figure 5 – Mean magnitude (no units), duration (months), intensity (no units) and frequency (transition events per decade) of dry-wet and wet-dry severe (threshold  $\pm 1.6$ ) hydrological (SSI) transitions for each catchment in the baseline period (1989–2018) using SimObs and SimRCM data. Note that the frequency of SimRCM transitions has been adjusted to account for the 12 RCMs to allow for direct comparison with SimObs.



280 **Figure 6 - Mean magnitude (no units), duration (months), intensity (no units) and frequency (transition events per decade) of dry-wet and wet-dry severe (threshold  $\pm 1.6$ ) meteorological (SPI) transitions for each catchment in the baseline period (1989–2018) using SimRCM data.**

Figure 7 shows the seasonality of transitions spatially, by mapping the modal season of transition occurrence at each catchment. We find a clear, and broadly expected difference between dry-wet and wet-dry transitions. Dry-wet transitions predominantly occur during the spring and summer whereas wet-dry transitions are more prevalent during the autumn, with some localised variations across catchments. This fits with expectations of UK hydrological regimes as spring and autumn are transitional seasons in the UK, when river flows tend to shift from drier to wetter states (or vice versa) – although of course these are modal seasons and transitions do occur at other times. Whereas there was good agreement between SimObs and SimRCM in the spatial patterns of the transition metrics, the timing of transitions is less well replicated in the SimRCM, both in general (Figure S2) and spatially (Figure 7). This has possible implications for projected transitions, suggesting that future projections using eFLaG data represent the number and extent of transitions well, but do not seem to capture the timing or seasonality of the transitions as accurately.

In comparison with hydrological transitions, meteorological transitions show a more pronounced difference in seasonality between the two directions (Figure 7), although still show a similar seasonality to hydrological transitions (dry-wet in spring, wet-dry in autumn/winter). Meteorological dry-wet transitions are far more spatially coherent in their seasonality, and in the wet-dry transitions we see a northwest-southeast gradient, reflecting the spatial pattern in rainfall distribution across the UK.

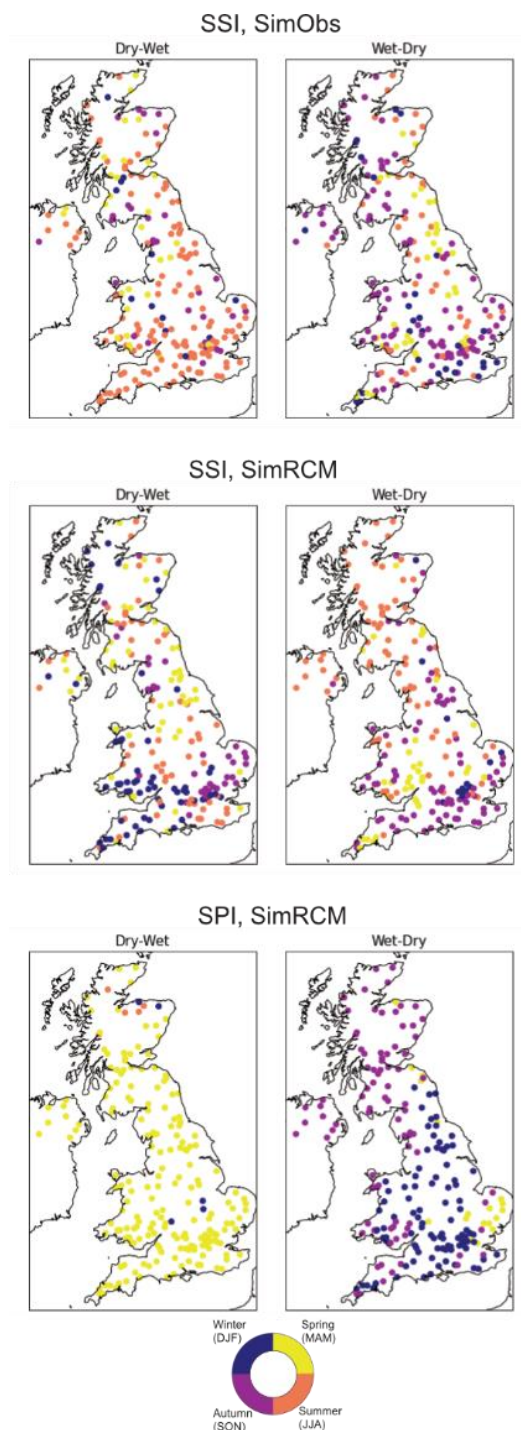


Figure 7 – Modal season of transition occurrence of dry-wet (left) and wet-dry (right) severe (threshold  $\pm 1.6$ ) hydrological (SSI) transitions in the baseline period (1989-2018) in SimObs (top) and SimRCM (bottom), using transition end month for dry-wet and wet-dry transitions.



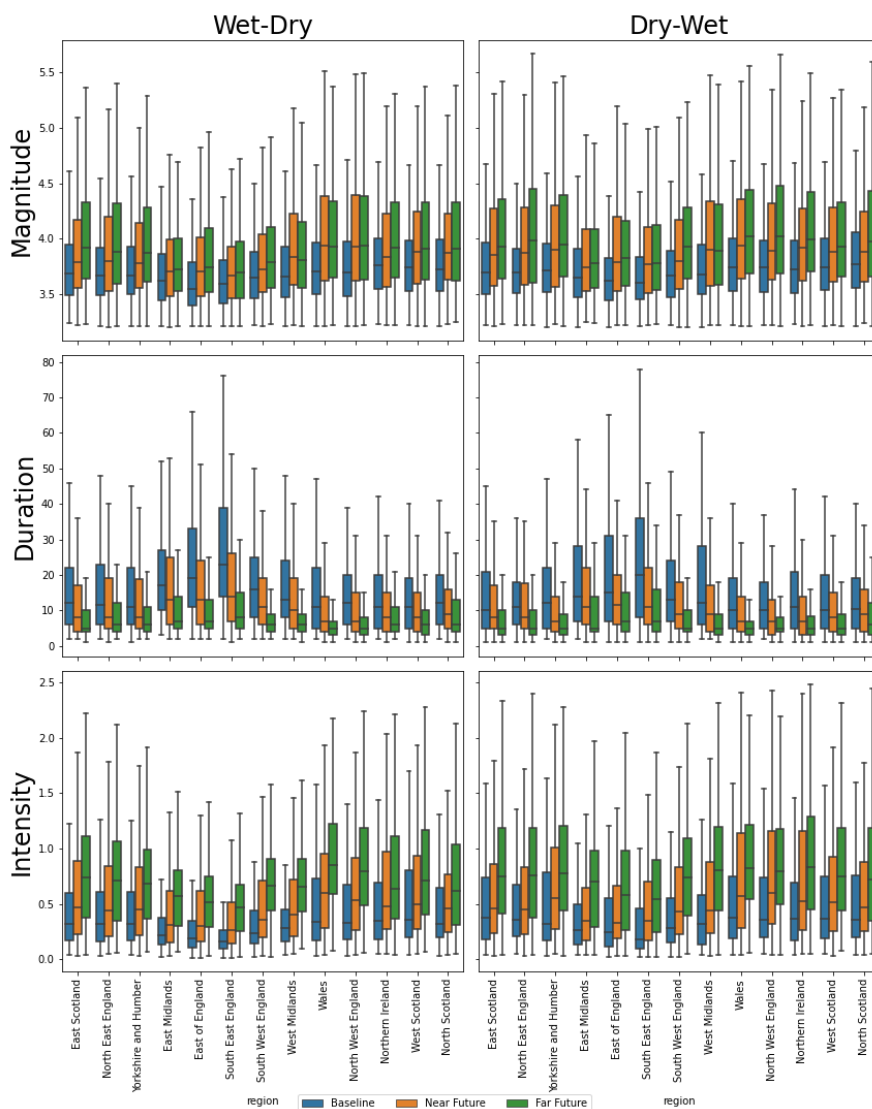
### 3.2. Future transitions

Figure 8 shows projected changes in transition metrics (magnitude, duration and intensity) as spread of the area averages over UK administrative regions to represent the ensemble uncertainty over the three time periods (BL, NF, FF). Transition magnitude is projected to increase for most regions of the UK between the baseline and far future period for both wet-dry and dry-wet transitions. For both directions of transition, all regions of the UK show decreased duration into the far future, although with some uncertainty in the magnitude of this decrease due to the overlapping ensemble/model spread. Increases in transition magnitude and decreased duration result in a projected increase in intensity across all regions of the UK (Figure 8). However, the projected changes are subject to large uncertainties, with substantial overlap in the ensemble distributions of transition magnitude and duration across present and future periods, suggesting that internal variability and uncertainty between different climate model parametrisations dominate the projected signal.

The projected changes in transition characteristics described here are broadly the same for both wet-dry and dry-wet transitions, suggesting that, whilst their characteristics in the historical period are different, their magnitude and direction of change under future climate projections are similar.

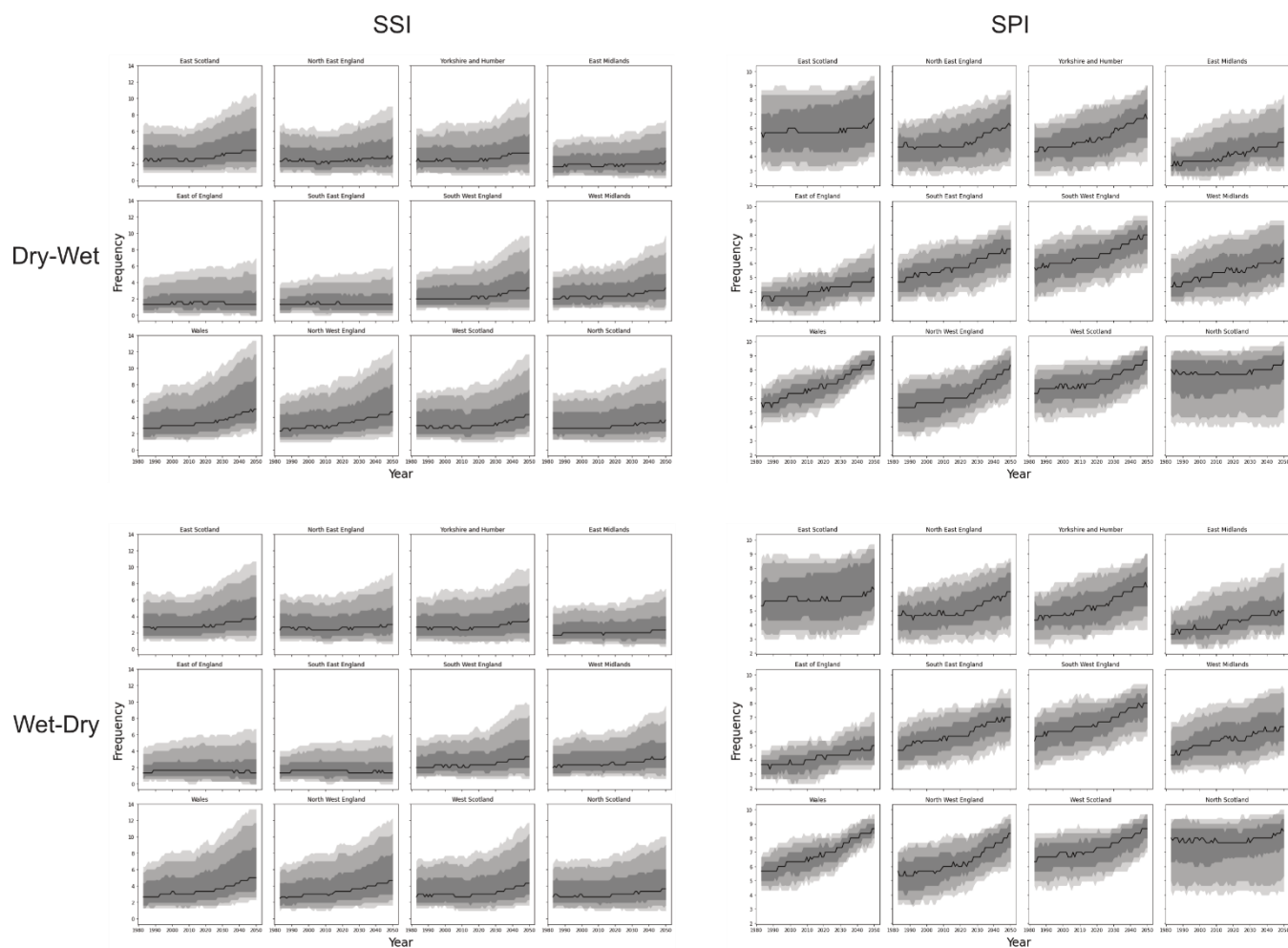
The largest decreases in transition duration are in southeastern catchments (East Midlands, East of England, and South East England) which had the longest duration initially due to the influence of groundwater and slow responding catchments. The decrease in transition duration indicates a shift from long multi-annual transitions in these regions towards seasonal switches between extremes, potentially the result of increased variability in a future climate, leading to more frequent and extreme swings away from average.

Transient changes in frequency of transitions over a 30-year moving window (Figure 9) show the most notable increases in hydrological transition frequency in northwestern areas (Wales and North West England) over the 21<sup>st</sup> century, whereas the ensemble mean for other regions generally show less dramatic changes, although ensemble spread remains large. Meteorological transitions show a clearer positive trend and a narrower ensemble spread for all regions, other than East Scotland and North Scotland. Increases in frequency in all regions for meteorological transitions but only in northwestern regions for hydrological transitions suggests that meteorological transitions do not directly translate into hydrological transitions in all regions, e.g. regions with slower responding catchments and more storage effectively 'buffer' the hydrological response. The large model spread points to large internal variability and uncertainty amongst ensemble members in the eFLaG simulations, suggesting that projected changes in transitions over most of the UK remain uncertain and highlighting the need for improved process understanding and alternative methods to better constrain future projections (see 4.1 for further discussion).



330

**Figure 8 – Boxplot representing region-averaged magnitude (no units), duration (months) and intensity (no units) of severe (threshold  $\pm 1.6$ ) wet-dry and dry-wet hydrological (SSI) transitions for baseline, near future and far future with SimRCM using GR6J model. The spread of the boxplots (ranging from 5<sup>th</sup>-95<sup>th</sup> percentile, without outliers) represents the 12 RCM scenarios.**



335

340

**Figure 9 – Frequency (number of transitions per decade) of severe (threshold  $\pm 1.6$ ) hydrological (SSI, left) and meteorological (SPI, right) dry-wet (top) and wet-dry (bottom) transitions using SimRCM for all models for whole period of study (1989-2079) for each region (excluding NI) calculated over a 30-year window, moving one year at a time. Shading shows the range of variability across hydrological models (for SSI only), RCMs and catchments within region, with the banding representing the 5-95<sup>th</sup>, 10-90<sup>th</sup> and 25-50<sup>th</sup> percentiles from lightest to darkest.**

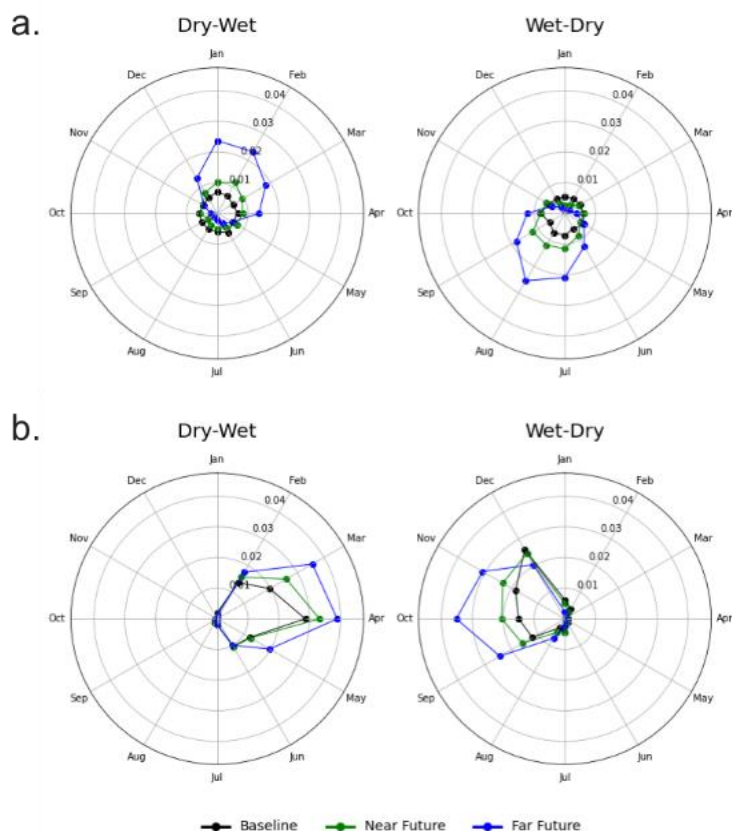
345

Figure 10 shows the proportion of transition events ending in each calendar month for the baseline, near future and far future periods for the whole of the UK, to assess the seasonality of transitions. We see a general increase in the number of transitions occurring in the future periods compared to baseline, along with a more pronounced seasonality of transitions. This may point to increasing extremes or volatility in the near-future period, in line with previous studies of individual extremes (Griffin et al., 2024; Parry et al., 2024), and a subsequent influence on transitions. Splitting transition events by direction shows a summer peak in wet-dry transitions and a winter peak in dry-wet transitions in future periods. Whilst we see a strengthening seasonality of transitions, the timing of the peak appears consistent into the future. Given the spatial distribution of transition metrics we find previously across the northwest and southeast of the UK, we assess the seasonality of transitions for two distinct regions (West Scotland, a northwestern region, Figure S3a and East of England, a southeastern region, Figure S3b). We see a clear



350 difference in the projected seasonality in the far future period for the two regions, with the region of faster responding  
catchments showing a far more pronounced seasonality. The peak in transition timing occurs mainly in January (dry-wet) and  
August (wet-dry) in the northwest, whilst there is more of a spread in the southeast with dry-wet transitions over spring and  
wet-dry over summer and autumn. Figure 10 also illustrates the projected increased number of transitions; both regions show  
an increase by the near future period, although the northwestern region then goes on to increase dramatically into the far future.  
355 Meteorological transitions also show a projected increased occurrence and stronger seasonality (Figure 10b), although with  
some key differences. There is generally a higher number of meteorological transitions occurring and the timing is slightly  
different than for hydrological transitions, with wet-dry meteorological transitions occurring in autumn and dry-wet in spring.  
This seasonality is already identifiable from the baseline period, much sooner than for hydrological transitions. This may be  
explained by the inherent lag between meteorological and hydrological extremes driven by underlying hydrological processes  
360 (Barker et al., 2016b), although further analysis would be required to fully explain the relationship between meteorological  
and hydrological transitions.

Although we do not see a notable difference between dry-wet and wet-dry hydrological transition characteristics into the future  
(Figure 8), there is a clear difference in their seasonality (Figure 10). This suggests that whilst changes in the two transition  
types are of similar scale and direction, their changes are occurring during different times of the year. Meteorological  
365 transitions also show minimal differences between characteristics of future wet-dry and dry-wet transitions, apart from for  
intensity which is lower for wet-dry transitions in some regions (Figure S4).



370 **Figure 10 – Seasonality of severe (threshold  $\pm 1.6$ ) a. hydrological (SSI) and b. meteorological (SPI) transitions using SimRCM for all models, shown as a fraction of transition events ending in each calendar month for baseline, near future and far future periods for dry-wet and wet-dry transitions.**

#### 4. Discussion

375 One of the key objectives of this study was to characterise current and future hydrological transitions in the UK, with a particular emphasis on the implications for water resource management. Current transitions are most common in northwestern UK where we also see the highest intensity transitions. Transitions in the southeast of the UK exhibit longer durations and subsequently lower intensities. The spatial patterns in our results indicate a strong association between hydrological and meteorological transitions in the UK, as shown in Brunner et al. (2025a) who find greatest propagation rates from meteorological to hydrological transitions for catchments in the UK. This is borne out by previous studies focusing on drought that also find a pronounced gradient in meteorological drought (e.g. Barker et al., 2016b; Folland et al., 2015) which is then further significantly amplified at a hydrological level. A more comprehensive characterisation of transitions over the historical period would necessitate the use of observed river flows or model-based reconstructions of river flows before instrumental records, which is beyond the scope of the current work.

380



Our results reveal some key differences between hydrological and meteorological transitions in the UK, namely a shorter duration and stronger seasonality of meteorological transitions in the baseline period, and an increase in frequency of meteorological transitions for all regions in future periods. Evaporative losses – which will increase in a warmer climate – will drive changes in river flows even without changes in precipitation. These differences between hydrological and meteorological transitions suggest that temperature may play a key role in transition occurrence, and transitions in SPEI, which accounts for evaporation, could be considered in further work.

There is a general consensus that hydroclimate volatility (encompassing transitions) is expected to increase in the future. Globally, the frequency of seasonal and interannual hydroclimate whiplash has been shown to increase with continued anthropogenic warming (Swain et al., 2025a). In Europe, projections show increases in the occurrence of summer droughts ending in heavy precipitation (Steensen et al., 2025); in North America, transitions between wet and dry spells will increase in frequency and intensity under further warming (Na and Najafi, 2024); and in South Asia, the intensity (and duration) of transitions from dry to wet periods are projected to increase (and decrease) (Chen and Wang, 2022). In future periods, our results show a projected increase in the frequency of transitions, with the most notable increases also in northwestern areas. Southeastern regions show the largest projected decreases in transition duration whilst intensity is projected to increase for all regions. In their assessment of future transitions under different warming levels, He et al. (2026) also show an increase in the frequency of transitions in northwestern areas of the UK, although do not consider other transition metrics (e.g. intensity) to characterise further. There is a broad similarity in results as both studies are underpinned by the UKCP18 projections. A recent study by Lane et al. (2026) comparing UKCP18 with EuroCORDEX-UK found UKCP18 future drought projections to be more severe than others, meaning that whilst they capture extreme scenarios, they may not capture the full range of uncertainties in future drought impacts. This may in turn lead to an overestimation of mean transition magnitude.

Most previous studies project an increase in intensity of both droughts and floods in the UK (Griffin et al., 2024; Parry et al., 2024) which would, in itself, result in larger magnitudes of transitions. This intensification of the hydrological cycle in response to warming is expected to increase variability in rainfall and river flows, and hydrological volatility globally (Hammond et al., 2025; Huntington, 2006; Lambert et al., 2025; Swain et al., 2025a). It should be noted that, under our methodology, an increase in the *number* of extreme events would not necessarily result in a corresponding increase in the number of transitions. If, into the future, we see more intense flood rich periods and drought periods becoming more drought prone, then this would not necessarily result in an increase in transition frequency. However, if, under climate change, we begin to see a more variable climate (more swings between wet and dry), this would result in an increase in the number of hydrological transitions. Our results of a general decrease in the duration of transitions, along with an increase in frequency, suggest a more unstable future climate with extremes more randomly distributed in time (Swain et al., 2025a).

Our results thus demonstrate the need for a change from traditional water resource management to embracing management across the flood/drought continuum. This echoes previous calls for increased preparedness to both extremes and the need to manage them in conjunction, both in the UK (Hall and Murgatroyd, 2025; Wagener et al., 2021) and internationally (Ward et al., 2020). On a short-term management timescale, improved monitoring and early warning systems, as well as risk



communication strategies, are needed to enable hydrological status to be tracked, forecasted and disseminated, and to integrate drought and flood response plans to identify potential linkages in mitigation responses (e.g. through adaptive reservoir management, Facincani Dourado et al., 2024). On a longer-term planning timescale, results highlight the benefits of improving storage in catchments to exploit increases in wet extremes to enhance resilience to subsequent dry episodes, both through  
420 reservoir development (as currently planned at a large scale across several areas of England) as well as through Natural Flood Management or Nature-Based Solutions (Kay et al., 2019). Infrastructure needs to be designed not only for more extreme or intense wet and dry events than currently specified, but also have flexibility built in to adapt for transitions and increasing hydrological volatility (Ficklin et al., 2022).

#### 4.1. Future Work

425 In this study, we use standardised indices at monthly timescales which emphasise seasonal transitions, commonly referred to as ‘state switches’ (e.g. Hammond et al., 2025). Seasonal transitions are particularly relevant for water resource availability and necessitate differences in management responses. Frequent transitions pose a challenge to the conjunctive management of anomalously wet and dry periods, with successive hazards often leading to higher impacts and reduced effectiveness of adaptation measures when compared with singular hazards. A focus on seasonal transitions also allows us to include wet-dry  
430 transitions, which are typically experienced at seasonal rather than short timescales (Muñoz-Castro et al., 2026). By contrast, identifying ‘true’ drought-flood transitions requires methods that capture much more rapid changes transitions (Götte and Brunner, 2024), which primarily affect ecological and environmental systems (van Vliet et al., 2023) rather than water resources. Further, drought-to-flood transitions identified using alternative methods may not alleviate long-term water deficits established during a drought period, as short-duration floods can occur during a drought and be followed by a rapid return to  
435 dry conditions (Barendrecht et al., 2024). Given the distinct impacts associated with different transition types, careful consideration of transition definition is essential when selecting appropriate methodologies (Anderson et al., 2025). Future work could compare our results with ‘true’ drought and flood transitions using the same dataset, enabling a direct cross-comparison.

##### 4.1.1. Drivers of transitions

440 The driving mechanisms behind transitions are generally not fully understood at present, although in places they have been linked to large scale atmospheric circulation patterns (e.g. atmospheric blocking; Brunner et al. 2025b, or shifts in atmospheric regimes; Francis et al., 2023). A comprehensive analysis of rapid drought termination across the British and Irish Isles found that the majority of termination events in the winter season are associated with atmospheric rivers and high integrated water vapour transport (IVT) driving intense rainfall (Parry et al., 2023). The association between high IVT and drought termination  
445 was most notable in the fast-responding upland catchments of the northwest. However, extensive studies focusing on the drivers of transitions has not been done yet in literature.



Future work could make use of hydrological simulations driven by initial condition large ensembles (e.g. Brunner, Swain, et al., 2021; Chan et al., 2025) to not only analyse a larger sample of transitions but also investigate the meteorological drivers of hydrological transitions and whether transitions in different regions are driven by common climate drivers or occur simply  
450 by chance due to large internal climate variability.

Results in this study use the eFLaG projections, which may under-sample overall uncertainty from both internal variability and between different climate model ensembles. This complicates our ability to disentangle the projected climate signal from internal variability and limits understanding of future scenario uncertainty. However, eFLaG is the only available dataset providing nationally consistent river flow projections with multiple hydrological models, making it the best option currently  
455 available. As new and improved hydrological projection datasets become available – for example, multi-model climate projections (e.g. Kay, 2025) or single model initial-condition large ensembles (SMILEs) – this provides an opportunity to better characterise different sources of uncertainties (i.e. climate model and internal variability) in future hydrological transitions (e.g. Na and Najafi, 2024). The different hydrological models within eFLaG represents hydrological processes in different ways and model performance over the historical period varies, with Aitken et al. (2023) showing a particularly large  
460 uncertainty in simulations of low flows between the models. The use of standardised indicators somewhat mitigates this by allowing consistent comparison between models. Future work could compare transition events identified using raw simulated flows for each model to investigate whether key hydrological processes are included in models to accurately capture the drivers, timing and intensity of hydrological transitions, building on existing work assessing how well models replicate hydrological extremes (e.g. McGrady et al., 2025) and their transitions (e.g. Muñoz-Castro et al., 2026).

## 465 5. Summary and Conclusions

In this study, we use nationally consistent river flow projections to evaluate the characteristics of historical and future hydrological transitions for the UK. Our analysis focuses on both the wet-dry and dry-wet transitions, drawing comparisons with the equivalent meteorological transitions.

We find a general spatial pattern for both hydrological and meteorological transitions in the historical period, with northwestern  
470 areas of the UK experiencing higher intensity and frequency of transitions compared to the southeast where we see the longest duration transitions. We also identify general timing of transitions in catchments across the UK, which should in turn allow for water managers to be better prepared for these transition events.

Our results show a projected increase in the intensity and occurrence of transitions across the UK in both near-future and far-future periods (although uncertainty remains in the timing (seasonality) of these changes) reflecting projected increases in  
475 hydrological volatility elsewhere/globally (Steensen et al., 2025; Swain et al., 2025a). The projected intensity and frequency of transitions is highest in northwestern regions whilst the largest changes in transition duration are seen in the south-east where baseline duration was the longest in the baseline period.



We have emphasised the importance for extreme wet and dry events to be considered together rather than in isolation but also shown the added value and relevance of considering wet-dry transitions as these transitions can be equally impactful and  
480 challenging to manage, and are just as common, as their dry-wet counterpart.

This study demonstrates the need to uptake adaptive water management measures in the UK to better cope with the challenges posed by hydrological transitions, and for further research into the drivers of hydrological transitions to increase process understanding and aid climate adaptation in an increasingly volatile hydroclimate.

### Acknowledgements

485 This research was funded by the Natural Environment Research Council CANARI project (NE/W004984/1), and the Co-Centre for Climate + Biodiversity + Water programme (NE/Y006496/1) funded by Science Foundation Ireland (SFI), Northern Ireland's Department of Agriculture, Environment and Rural Affairs (DAERA) and UK Research and Innovation (UKRI).

### Data Availability

The eFLaG data used in this study is openly available at <https://doi.org/10.5285/1bb90673-ad37-4679-90b9-0126109639a9>.  
490 The eFLaG Portal allows users to explore the full 200 eFLaG catchments rather than just the subset used here (<https://eip.ceh.ac.uk/hydrology/eflag>, UKCEH, 2022). SPI over the historical period can be downloaded from the UK Water Resources Portal ([ukwrp.ceh.ac.uk](http://ukwrp.ceh.ac.uk); Barker et al., 2022).

### Author Contributions

**Rachael Armitage** – conceptualisation, formal analysis, visualisation, writing (original draft); **Eugene Magee** –  
495 conceptualisation, formal analysis, visualisation, writing (review and editing); **Amulya Chevuturi** – conceptualisation, supervision, writing (review and editing); **Wilson Chan** – data curation, writing (review and editing); **Jamie Hannaford** – funding acquisition, supervision, writing (review and editing)

### References

Aitken, G., Beevers, L., Parry, S., and Facer-Childs, K.: Partitioning model uncertainty in multi-model ensemble river flow  
500 projections, *Climatic Change* 2023 176:11, 176, 153-, <https://doi.org/10.1007/S10584-023-03621-1>, 2023.  
Anderson, B. J., Muñoz-Castro, E., Tallaksen, L. M., Matano, A., Götte, J., Armitage, R., Magee, E., and Brunner, M. I.: What is a drought-to-flood transition? Pitfalls and recommendations for defining consecutive hydrological extreme events, <https://doi.org/10.5194/EGUSPHERE-2025-1391>, 2025.



- Barendrecht, M. H., Matanó, A., Mendoza, H., Weesie, R., Rohse, M., Koehler, J., de Rooter, M., Garcia, M., Mazzoleni, M.,  
505 Aerts, J. C. J. H., Ward, P. J., Di Baldassarre, G., Day, R., and Van Loon, A. F.: Exploring drought-to-flood interactions and  
dynamics: A global case review, *Wiley Interdisciplinary Reviews: Water*, 11, e1726, <https://doi.org/10.1002/WAT2.1726>,  
2024.
- Barker, L., Hannaford, J., Muchan, K., Turner, S., and Parry, S.: The winter 2015/2016 floods in the UK: a hydrological  
appraisal, *Weather*, 71, 324–333, <https://doi.org/10.1002/wea.2822>, 2016a.
- 510 Barker, L. J., Hannaford, J., Chiverton, A., and Svensson, C.: From meteorological to hydrological drought using standardised  
indicators, *Hydrol. Earth Syst. Sci*, 20, 2483–2505, <https://doi.org/10.5194/hess-20-2483-2016>, 2016b.
- Barker, L. J., Fry, M., Hannaford, J., Nash, G., Tanguy, M., and Swain, O.: Dynamic High Resolution Hydrological Status  
Monitoring in Real-Time: The UK Water Resources Portal, *Front. Environ. Sci.*, 10, 752201,  
<https://doi.org/10.3389/FENVS.2022.752201/BIBTEX>, 2022.
- 515 Barker, L. J., Hannaford, J., Magee, E., Turner, S., Sefton, C., Parry, S., Evans, J., Szczykulska, M., and Haxton, T.: An  
appraisal of the severity of the 2022 drought and its impacts, *Weather*, 79, 208–219,  
<https://doi.org/10.1002/WEA.4531>;CTYPE:STRING:JOURNAL, 2024.
- Bell, V. A., Kay, A. L., Jones, R. G., and Moore, R. J.: Use of a grid-based hydrological model and regional climate model  
outputs to assess changing flood risk, *International Journal of Climatology*, 27, 1657–1671,  
520 <https://doi.org/10.1002/JOC.1539>;WGROU:STRING:PUBLICATION, 2007.
- Brunner, M. I.: Floods and droughts: a multivariate perspective, *Hydrol. Earth Syst. Sci.*, 27, 2479–2497,  
<https://doi.org/10.5194/HESS-27-2479-2023>, 2023.
- Brunner, M. I., Swain, D. L., Wood, R. R., Willkofer, F., Done, J. M., Gilleland, E., and Ludwig, R.: An extremeness threshold  
determines the regional response of floods to changes in rainfall extremes, *Commun. Earth Environ.*, 2, 1–11,  
525 [https://doi.org/10.1038/S43247-021-00248-](https://doi.org/10.1038/S43247-021-00248-X)  
X;SUBJMETA=106,242,2739,35,4111,694,704;KWRD=ATMOSPHERIC+SCIENCE,CLIMATE-  
CHANGE+IMPACTS,HYDROLOGY,NATURAL+HAZARDS, 2021a.
- Brunner, M. I., Slater, L., Tallaksen, L. M., and Clark, M.: Challenges in modeling and predicting floods and droughts: A  
review, *Wiley Interdisciplinary Reviews: Water*, 8, e1520,  
530 <https://doi.org/10.1002/WAT2.1520>;REQUESTEDJOURNAL:JOURNAL:20491948;PAGEGROUP:STRING:PUBLICATION,  
2021b.
- Brunner, M. I., Anderson, B., and Muñoz-Castro, E.: Meteorological and hydrological dry-to-wet transition events are only  
weakly related over European catchments, *Environmental Research Letters*, <https://doi.org/10.1088/1748-9326/ADE72C>,  
2025a.
- 535 Brunner, M. I., Mittermeier, M., Anderson, B., Büeler, D., and Muñoz-Castro, E.: Spatially Compounding Drought-Flood  
Events Are Favored by Atmospheric Blocking Over Europe, *Water Resour. Res.*, 61, e2024WR039622,  
<https://doi.org/10.1029/2024WR039622>, 2025b.



- Chan, W., Tanguy, M., Chevuturi, A., and Hannaford, J.: Climate variability conceals emerging hydrological trends across Great Britain, *J. Hydrol. (Amst)*, 660, 133414, <https://doi.org/10.1016/J.JHYDROL.2025.133414>, 2025a.
- 540 Chan, W. C. H., Barker, L. J., Faranda, D., and Hannaford, J.: River flow amplification under climate change: attribution and climate-driven storylines of the winter 2023/24 UK floods, *Environmental Research Letters*, 20, 104035, <https://doi.org/10.1088/1748-9326/ADDFE>, 2025b.
- Chen, H. and Wang, S.: Accelerated Transition Between Dry and Wet Periods in a Warming Climate, *Geophys. Res. Lett.*, 49, e2022GL099766, <https://doi.org/10.1029/2022GL099766>, 2022.
- 545 Chen, L. and Ford, T. W.: Future changes in the transitions of monthly-to-seasonal precipitation extremes over the Midwest in Coupled Model Intercomparison Project Phase 6 models, *International Journal of Climatology*, 43, 255–274, <https://doi.org/10.1002/JOC.7756>, 2023.
- Coles, N. A. and Eslamian, S.: Definition of Drought, in: *Handbook of Drought and Water Scarcity*, CRC Press, 1–11, <https://doi.org/10.1201/9781315404219-1>, 2017.
- 550 Collet, L., Harrigan, S., Prudhomme, C., Formetta, G., and Beevers, L.: Future hot-spots for hydro-hazards in Great Britain: A probabilistic assessment, *Hydrol. Earth Syst. Sci.*, 22, 5387–5401, <https://doi.org/10.5194/HESS-22-5387-2018>, 2018.
- DeGaetano, A. T. and Lim, L. S.: Declining U.S. regional and continental trends in intra-annual and interannual extreme temperature swings, *International Journal of Climatology*, 40, 2830–2844, <https://doi.org/10.1002/JOC.6369>, 2020.
- Van Dijk, A. I. J. M., Beck, H. E., Crosbie, R. S., De Jeu, R. A. M., Liu, Y. Y., Podger, G. M., Timbal, B., and Viney, N. R.:
- 555 The Millennium Drought in southeast Australia (2001–2009): Natural and human causes and implications for water resources, ecosystems, economy, and society, *Water Resour. Res.*, 49, 1040–1057, <https://doi.org/10.1002/WRCR.20123>;REQUESTEDJOURNAL:JOURNAL:19447973;WGROU:STRING:PUBLICATION, 2013.
- Eslamian, S. and Eslamian, F.: *Flood Handbook*, CRC Press, Boca Raton, <https://doi.org/10.1201/9781003262640>, 2022.
- 560 Facincani Dourado, G., Rheinheimer, D. E., Abatzoglou, J. T., and Viers, J. H.: Stress Testing California’s Hydroclimatic Whiplash: Potential Challenges, Trade-Offs and Adaptations in Water Management and Hydropower Generation, *Water Resour. Res.*, 60, e2023WR035966, <https://doi.org/10.1029/2023WR035966>, 2024.
- Ficklin, D. L., Null, S. E., Abatzoglou, J. T., Novick, K. A., and Myers, D. T.: Hydrological Intensification Will Increase the Complexity of Water Resource Management, *Earths Future*, 10, e2021EF002487, <https://doi.org/10.1029/2021EF002487>,
- 565 2022.
- Pakistan – Almost 1,000 Dead, 33 Million Affected in Worst Floods in a Decade – FloodList: <https://floodlist.com/asia/pakistan-floods-update-august-2022>, last access: 19 August 2025.
- Folland, C. K., Hannaford, J., Bloomfield, J. P., Kendon, M., Svensson, C., Marchant, B. P., Prior, J., and Wallace, E.: Multi-annual droughts in the English Lowlands: A review of their characteristics and climate drivers in the winter half-year, *Hydrol. Earth Syst. Sci.*, 19, 2353–2375, <https://doi.org/10.5194/HESS-19-2353-2015>, 2015.
- 570

Ford, T. W., Chen, L., and Schoof, J. T.: Variability and Transitions in Precipitation Extremes in the Midwest United States, *J. Hydrometeorol.*, 22, 533–545, <https://doi.org/10.1175/JHM-D-20-0216.1>, 2021.

Francis, J. A., Skific, N., and Zobel, Z.: Weather whiplash events in Europe and North Atlantic assessed as continental-scale atmospheric regime shifts, *npj Climate and Atmospheric Science* 2023 6:1, 6, 216–, <https://doi.org/10.1038/s41612-023-00542-9>, 2023.

Götte, J. and Brunner, M. I.: Hydrological Drought-To-Flood Transitions Across Different Hydroclimates in the United States, *Water Resour. Res.*, 60, e2023WR036504, <https://doi.org/10.1029/2023WR036504>, 2024.

Griffin, A., Kay, A. L., Sayers, P., Bell, V., Stewart, E., and Carr, S.: Widespread flooding dynamics under climate change: characterising floods using grid-based hydrological modelling and regional climate projections, *Hydrol. Earth Syst. Sci.*, 28, 2635–2650, <https://doi.org/10.5194/HESS-28-2635-2024>, 2024.

Griffin, A., Vesuviano, G., Wilson, D., Sefton, C., Turner, S., Armitage, R., and Suman, G.: Putting the English Flooding of 2019–2021 in the Context of Antecedent Conditions, *J. Flood Risk Manag.*, 18, e70016, <https://doi.org/10.1111/jfr3.70016>, 2025.

Hall, J. W. and Murgatroyd, A.: Adapting water resource systems to a changing future: Challenges for UK hydrology in the 21st century, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 383, <https://doi.org/10.1098/RSTA.2024.0278/234775>, 2025.

Hammond, J., Anderson, B., Simeone, C., Brunner, M., Muñoz-Castro, E., Archfield, S., Magee, E., and Armitage, R.: Hydrological Whiplash: Highlighting the Need for Better Understanding and Quantification of Sub-Seasonal Hydrological Extreme Transitions, *Hydrol. Process.*, 39, e70113, <https://doi.org/10.1002/HYP.70113;SUBPAGE:STRING:FULL>, 2025.

Hannaford, J., Mackay, J., Ascott, M., Bell, V., Chitson, T., Cole, S., Counsell, C., Durant, M., Facer-Childs, K., Jackson, C., Kay, A., Lane, R., Mansour, M., Moore, R. J., Parry, S., Rudd, A., Simpson, M., Turner, S., Wallbank, J., Wells, S., and Wilcox, A.: Hydrological projections for the UK, based on UK Climate Projections 2018 (UKCP18) data, from the Enhanced Future Flows and Groundwater (eFLaG) project, NERC EDS Environmental Information Data Centre, <https://doi.org/10.5285/1bb90673-ad37-4679-90b9-0126109639a9>, 2022.

Hannaford, J., Mackay, J. D., Ascott, M., Bell, V. A., Chitson, T., Cole, S., Counsell, C., Durant, M., Jackson, C. R., Kay, A. L., Lane, R. A., Mansour, M., Moore, R., Parry, S., Rudd, A. C., Simpson, M., Facer-Childs, K., Turner, S., Wallbank, J. R., Wells, S., and Wilcox, A.: The enhanced future Flows and Groundwater dataset: development and evaluation of nationally consistent hydrological projections based on UKCP18, *Earth Syst. Sci. Data*, 15, 2391–2415, <https://doi.org/10.5194/essd-15-2391-2023>, 2023.

600 Guest post: Is climate change making UK droughts worse? - Carbon Brief: <https://www.carbonbrief.org/guest-post-is-climate-change-making-uk-droughts-worse/>, last access: 25 March 2026.

Hannaford, J., Turner, S., Chevuturi, A., Chan, W., Barker, L. J., Tanguy, M., Parry, S., and Allen, S.: Have river flow droughts become more severe? A review of the evidence from the UK - A data-rich, temperate environment, *Hydrol. Earth Syst. Sci.*, 29, 4371–4394, <https://doi.org/10.5194/hess-29-4371-2025>, 2025.



- 605 He, X. and Sheffield, J.: Lagged Compound Occurrence of Droughts and Pluvials Globally Over the Past Seven Decades, *Geophys. Res. Lett.*, 47, e2020GL087924, <https://doi.org/10.1029/2020GL087924>, 2020.
- He, Y., Manful, D., Forstenhäusler, N., Huang, Y., Smith, B., and Zha, Q.: Escalating Hydroclimatic Extremes and Volatility in the UK Under 2 Degrees C and 4 Degrees C Warming, *Earths Future*, 2026.
- Hollis, D., McCarthy, M., Kendon, M., Legg, T., and Simpson, I.: HadUK-Grid—A new UK dataset of gridded climate  
610 observations, *Geosci. Data J.*, 6, 151–159, <https://doi.org/10.1002/GDJ3.78>, 2019.
- Huntington, T. G.: Evidence for intensification of the global water cycle: Review and synthesis, *J. Hydrol. (Amst.)*, 319, 83–95, <https://doi.org/10.1016/J.JHYDROL.2005.07.003>, 2006.
- IPCC: IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)].  
615 IPCC, Geneva, Switzerland., <https://doi.org/10.59327/IPCC/AR6-9789291691647>, 2023.
- Jaroszweski, D., Wood, R., Chapman, L., Bell, S., Betts, R., Darch, G., Ferranti, E., Gosling, S., Haigh, I., Hughes, P., Lombardi, D., Palin, E., Paulson, K., Pregnolato, M., Watson, G., White, D., Watkiss, P., Bell, A., Berman, J., Brown, K., Holmes, G., Hurst, M., Knowles, R., Labuschagne, C., Mair, R., Mccullough, J., Netherwood, A., Payne, C., Russell, A., and Style, D.: Third UK Climate Change Risk Assessment Technical Report , 2021.
- 620 Kay, A. L.: A comparison of hydrological impacts from two ensembles of regional climate projections with a range of climate sensitivities, *Regional Environmental Change* 2025 25:3, 25, 89-, <https://doi.org/10.1007/s10113-025-02426-5>, 2025.
- Kay, A. L., Old, G. H., Bell, V. A., Davies, H. N., and Trill, E. J.: An assessment of the potential for natural flood management to offset climate change impacts, *Environmental Research Letters*, 14, 044017, <https://doi.org/10.1088/1748-9326/AAFDDBE>, 2019.
- 625 Kendon, M., Marsh, T., and Parry, S.: The 2010-2012 drought in England and Wales, *Weather*, 68, 88–95, <https://doi.org/10.1002/WEA.2101;CTYPE:STRING:JOURNAL>, 2013.
- Khan, N., Nguyen, H. T. T., Galelli, S., and Cherubini, P.: Increasing Drought Risks Over the Past Four Centuries Amidst Projected Flood Intensification in the Kabul River Basin (Afghanistan and Pakistan)—Evidence From Tree Rings, *Geophys. Res. Lett.*, 49, e2022GL100703, <https://doi.org/10.1029/2022GL100703;PAGE:STRING:ARTICLE/CHAPTER>, 2022.
- 630 Kreibich, H., Van Loon, A. F., Schröter, K., Ward, P. J., Mazzoleni, M., Sairam, N., Abeshu, G. W., Agafonova, S., AghaKouchak, A., Aksoy, H., Alvarez-Garreton, C., Aznar, B., Balkhi, L., Barendrecht, M. H., Biancamaria, S., Bos-Burgering, L., Bradley, C., Budiyo, Y., Buytaert, W., Capewell, L., Carlson, H., Cavus, Y., Couasnon, A., Coxon, G., Daliakopoulos, I., de Ruiter, M. C., Delus, C., Erfurt, M., Esposito, G., François, D., Frappart, F., Freer, J., Frolova, N., Gain, A. K., Grillakis, M., Grima, J. O., Guzmán, D. A., Huning, L. S., Ionita, M., Kharlamov, M., Khoi, D. N., Kieboom, N.,  
635 Kireeva, M., Koutroulis, A., Lavado-Casimiro, W., Li, H. Y., LLasat, M. C., Macdonald, D., Mård, J., Mathew-Richards, H., McKenzie, A., Mejia, A., Mendiondo, E. M., Mens, M., Mobini, S., Mohor, G. S., Nagavciuc, V., Ngo-Duc, T., Thao Nguyen Huynh, T., Nhi, P. T. T., Petrucci, O., Nguyen, H. Q., Quintana-Seguí, P., Razavi, S., Ridolfi, E., Riegel, J., Sadik, M. S., Savelli, E., Sazonov, A., Sharma, S., Sörensen, J., Arguello Souza, F. A., Stahl, K., Steinhausen, M., Stoelzle, M., Szalińska,



- W., Tang, Q., Tian, F., Tokarczyk, T., Tovar, C., Tran, T. V. T., Van Huijgevoort, M. H. J., van Vliet, M. T. H., Vorogushyn,  
640 S., Wagener, T., Wang, Y., Wendt, D. E., Wickham, E., Yang, L., Zambrano-Bigiarini, M., Blöschl, G., and Di Baldassarre,  
G.: The challenge of unprecedented floods and droughts in risk management, *Nature*, 608, 80–86,  
[https://doi.org/10.1038/S41586-022-04917-](https://doi.org/10.1038/S41586-022-04917-5)  
5;TECHMETA=141;SUBJMETA=242,4111,704;KWRD=HYDROLOGY,NATURAL+HAZARDS, 2022.
- Lambert, F. H., Allan, R. P., Behrangi, A., Byrne, M. P., Ceppi, P., Chadwick, R., Durack, P. J., Fossier, G., Fowler, H. J.,  
645 Greve, P., Lee, T., Mutton, H., O’Gorman, P. A., Osborne, J. M., Pendergrass, A. G., Reager, J. T., Stier, P., Swann, A. L. S.,  
Todd, A., Vicente-Serrano, S. M., and Stephens, G. L.: Changes in the Regional Water Cycle and Their Impact on Societies,  
*Wiley Interdiscip. Rev. Clim. Change*, 16, e70005, <https://doi.org/10.1002/WCC.70005>, 2025.
- Lane, R. A. and Kay, A. L.: Climate Change Impact on the Magnitude and Timing of Hydrological Extremes Across Great  
Britain, *Frontiers in Water*, 3, 684982, <https://doi.org/10.3389/frwa.2021.684982>, 2021.
- 650 Lane, R. A., Rudd, A. C., and Kay, A. L.: Climate change impact on hydrological droughts: Differences between two  
ensembles of regional climate projections across Great Britain, *J. Hydrol. Reg. Stud.*, 65, 103417,  
<https://doi.org/10.1016/J.EJRH.2026.103417>, 2026.
- Leonard, M., Westra, S., Phatak, A., Lambert, M., van den Hurk, B., McInnes, K., Risbey, J., Schuster, S., Jakob, D., and  
Stafford-Smith, M.: A compound event framework for understanding extreme impacts, *Wiley Interdiscip. Rev. Clim. Change*,  
655 5, 113–128, <https://doi.org/10.1002/WCC.252>;PAGEGROUP:STRING:PUBLICATION, 2014.
- Lowe, J. A., Bernie, D., Bett, P., Bricheno, L., Brown, S., Calvert, D., Clark, R., Eagle, K., Edwards, T., Fossier, G., Fung, F.,  
Gohar, L., Good, P., Gregory, J., Harris, G., Howard, T., Kaye, N., Kendon, E., Krijnen, J., Maisey, P., McDonald, R., McInnes,  
R., McSweeney, C., Mitchell, J. F., Murphy, J., Palmer, M., Roberts, C., Rostron, J., Sexton, D., Thornton, H., Tinker, J.,  
Tucker, S., Yamazaki, K., and Belcher, S.: UKCP18 Science Overview Report, 2018.
- 660 MacMahon, A., Smith, K., and Lawrence, G.: Connecting resilience, food security and climate change: lessons from flooding  
in Queensland, Australia, *J. Environ. Stud. Sci.*, 5, 378–391, <https://doi.org/10.1007/S13412-015-0278-0/TABLES/1>, 2015.
- Matanó, A., de Ruiter, M. C., Koehler, J., Ward, P. J., and Van Loon, A. F.: Caught Between Extremes: Understanding Human-  
Water Interactions During Drought-To-Flood Events in the Horn of Africa, *Earths Future*, 10, e2022EF002747,  
<https://doi.org/10.1029/2022EF002747>, 2022.
- 665 Matanó, A., Berghuijs, W. R., Mazzoleni, M., de Ruiter, M. C., Ward, P. J., and Van Loon, A. F.: Compound and consecutive  
drought-flood events at a global scale, *Environmental Research Letters*, 19, 064048, [https://doi.org/10.1088/1748-](https://doi.org/10.1088/1748-9326/AD4B46)  
9326/AD4B46, 2024.
- McGrady, E. L., Birkinshaw, S. J., Lewis, E., Smith, B. A., Walsh, C. L., Darch, G., and Dearlove, J.: Autocalibration of a  
physically-based hydrological model: does it produce physically realistic parameters?, *EGUsphere*, 1–41,  
670 <https://doi.org/10.5194/EGUSPHERE-2025-1824>, 2025.
- Mckee, T. B., Doesken, N. J., and Kleist, J.: The relationship of drought frequency and duration to time scales, in: Eighth  
Conference on Applied Climatology, 179–183, 1993.



- Miller, J. D., Kjeldsen, T. R., Hannaford, J., and Morris, D. G.: A hydrological assessment of the November 2009 floods in Cumbria, UK, *Hydrology Research*, 44, 180–197, <https://doi.org/10.2166/nh.2012.076>, 2013.
- 675 Moore, R. J.: The PDM rainfall-runoff model, *Hydrol. Earth Syst. Sci.*, 11, 483–499, <https://doi.org/10.5194/HESS-11-483-2007>, 2007.
- Muñoz-Castro, E., Anderson, B. J., Astagneau, P. C., Swain, D. L., Mendoza, P. A., and Brunner, M. I.: How well do hydrological models simulate streamflow extremes and drought-to-flood transitions?, *Hydrol. Earth Syst. Sci.*, 30, 825–848, <https://doi.org/10.5194/hess-30-825-2026>, 2026.
- 680 Na, W. and Najafí, M. R.: Rising risks of hydroclimatic swings: A large ensemble study of dry and wet spell transitions in North America, *Glob. Planet. Change*, 238, 104476, <https://doi.org/10.1016/J.GLOPLACHA.2024.104476>, 2024.
- Parry, S., Marsh, T., and Kendon, M.: 2012: from drought to floods in England and Wales, *Weather*, 68, 268–274, <https://doi.org/10.1002/WEA.2152>, 2013.
- Parry, S., Wilby, L. R., Prudhomme, C., and Wood, J. P.: A systematic assessment of drought termination in the United  
685 Kingdom, *Hydrol. Earth Syst. Sci.*, 20, 4265–4281, <https://doi.org/10.5194/HESS-20-4265-2016>, 2016a.
- Parry, S., Prudhomme, C., Wilby, R. L., and Wood, P. J.: Drought termination: Concept and characterisation, *Prog. Phys. Geogr.*, 40, 743–767, [https://doi.org/10.1177/0309133316652801/ASSET/F8E4B14A-41C6-45BE-B9A0-31E44207AD19/ASSETS/IMAGES/LARGE/10.1177\\_0309133316652801-FIG5.JPG](https://doi.org/10.1177/0309133316652801/ASSET/F8E4B14A-41C6-45BE-B9A0-31E44207AD19/ASSETS/IMAGES/LARGE/10.1177_0309133316652801-FIG5.JPG), 2016b.
- Parry, S., Lavers, D., Wilby, R., Prudhomme, C., Wood, P., Murphy, C., and O’Connor, P.: Abrupt drought termination in the  
690 British–Irish Isles driven by high atmospheric vapour transport, *Environmental Research Letters*, 18, 104050, <https://doi.org/10.1088/1748-9326/ACF145>, 2023.
- Parry, S., MacKay, J. D., Chitson, T., Hannaford, J., Magee, E., Tanguy, M., Bell, V. A., Facer-Childs, K., Kay, A., Lane, R., Moore, R. J., Turner, S., and Wallbank, J.: Divergent future drought projections in UK river flows and groundwater levels, *Hydrol. Earth Syst. Sci.*, 28, 417–440, <https://doi.org/10.5194/HESS-28-417-2024>, 2024.
- 695 Perrin, C., Michel, C., and Andréassian, V.: Improvement of a parsimonious model for streamflow simulation, *J. Hydrol. (Amst.)*, 279, 275–289, [https://doi.org/10.1016/S0022-1694\(03\)00225-7](https://doi.org/10.1016/S0022-1694(03)00225-7), 2003.
- Pushpalatha, R., Perrin, C., Le Moine, N., Mathevet, T., and Andréassian, V.: A downward structural sensitivity analysis of hydrological models to improve low-flow simulation, *J. Hydrol. (Amst.)*, 411, 66–76, <https://doi.org/10.1016/J.JHYDROL.2011.09.034>, 2011.
- 700 Rodda, J. C. and Marsh, T. J.: The 1975-76 Drought - a contemporary and retrospective review, National Hydrological Monitoring Programme series, NERC/Centre for Ecology & Hydrology, 1–8 pp., 2011.
- Shaw, C. and Corner, A.: Communicating drought risk in a changing climate, 2016.
- Steensen, B. M., Myhre, G., Hodnebrog, Ø., and Fischer, E.: Future increase in European compound events where droughts end in heavy precipitation, *npj Climate and Atmospheric Science* 2025 8:1, 8, 1–7, <https://doi.org/10.1038/s41612-025-01139-0>, 2025.
- 705 0, 2025.



- Svensson, C., Hannaford, J., and Prosdocimi, I.: Statistical distributions for monthly aggregations of precipitation and streamflow in drought indicator applications, *Water Resour. Res.*, 53, 999–1018, <https://doi.org/10.1002/2016WR019276>, 2017.
- Swain, D. L., Prein, A. F., Abatzoglou, J. T., Albano, C. M., Brunner, M., Diffenbaugh, N. S., Singh, D., Skinner, C. B., and  
710 Touma, D.: Hydroclimate volatility on a warming Earth, *Nature Reviews Earth & Environment* 2025 6:1, 6, 35–50, <https://doi.org/10.1038/s43017-024-00624-z>, 2025a.
- Swain, D. L., Abatzoglou, J. T., Albano, C. M., Brunner, M. I., Diffenbaugh, N. S., Kolden, C., Prein, A. F., Singh, D., Skinner, C. B., Swetnam, T. W., and Touma, D.: Increasing Hydroclimatic Whiplash Can Amplify Wildfire Risk in a Warming Climate, *Glob. Chang. Biol.*, 31, e70075, <https://doi.org/10.1111/GCB.70075>, 2025b.
- 715 Tanguy, M., Chevuturi, A., Marchant, B. P., Mackay, J. D., Parry, S., and Hannaford, J.: How will climate change affect the spatial coherence of streamflow and groundwater droughts in Great Britain?, *Environmental Research Letters*, 18, 064048, <https://doi.org/10.1088/1748-9326/ACD655>, 2023.
- Turner, S., Barker, L. J., Hannaford, J., Muchan, K., Parry, S., and Sefton, C.: The 2018/2019 drought in the UK: a hydrological appraisal, *Weather*, 76, 248–253, <https://doi.org/10.1002/WEA.4003;CTYPE:STRING:JOURNAL>, 2021.
- 720 Valenzuela, R., Garreaud, R., Vergara, I., Campos, D., Viale, M., and Rondanelli, R.: An extraordinary dry season precipitation event in the subtropical Andes: Drivers, impacts and predictability, *Weather Clim. Extrem.*, 37, 100472, <https://doi.org/10.1016/J.WACE.2022.100472>, 2022.
- van Vliet, M. T. H., Thorslund, J., Stokal, M., Hofstra, N., Flörke, M., Ehalt Macedo, H., Nkwasa, A., Tang, T., Kaushal, S. S., Kumar, R., van Griensven, A., Bouwman, L., and Mosley, L. M.: Global river water quality under climate change and  
725 hydroclimatic extremes, *Nature Reviews Earth & Environment* 2023 4:10, 4, 687–702, <https://doi.org/10.1038/s43017-023-00472-3>, 2023.
- Wagener, T., Dadson, S. J., Hannah, D. M., Coxon, G., Beven, K., Bloomfield, J. P., Buytaert, W., Cloke, H., Bates, P., Holden, J., Parry, L., Lamb, R., Chappell, N. A., Fry, M., and Old, G.: Knowledge gaps in our perceptual model of Great Britain’s hydrology, *Hydrol. Process.*, 35, e14288, <https://doi.org/10.1002/HYP.14288>, 2021.
- 730 Ward, P. J., de Ruiter, M. C., Mård, J., Schröter, K., Van Loon, A., Veldkamp, T., von Uexkull, N., Wanders, N., AghaKouchak, A., Arnbjerg-Nielsen, K., Capewell, L., Carmen Llasat, M., Day, R., Dewals, B., Di Baldassarre, G., Huning, L. S., Kreibich, H., Mazzoleni, M., Savelli, E., Teutschbein, C., van den Berg, H., van der Heijden, A., Vincken, J. M. R., Waterloo, M. J., and Wens, M.: The need to integrate flood and drought disaster risk reduction strategies, *Water Secur.*, 11, 100070, <https://doi.org/10.1016/J.WASEC.2020.100070>, 2020.
- 735 Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R. M., van den Hurk, B., AghaKouchak, A., Jézéquel, A., Mahecha, M. D., Maraun, D., Ramos, A. M., Ridder, N. N., Thiery, W., and Vignotto, E.: A typology of compound weather and climate events, *Nat. Rev. Earth Environ.*, 1, 333–347, <https://doi.org/10.1038/S43017-020-0060-Z;SUBJMETA=106,2739,35,694,704;KWRD=ATMOSPHERIC+SCIENCE,CLIMATE-CHANGE+IMPACTS,CLIMATE+SCIENCES>, 2020.

<https://doi.org/10.5194/egusphere-2026-3154>

Preprint. Discussion started: 11 June 2026

© Author(s) 2026. CC BY 4.0 License.



740