Rudd, Alison C.; Kay, A.L.; Bell, V.A. 2019. **National-scale analysis of future river flow and soil moisture droughts: potential changes in drought characteristics**.

This is a post-peer-review, pre-copyedit version of an article published in *Climatic Change*, 156 (3). 323-340. The final authenticated version is available online at: https://doi.org/10.1007/s10584-019-02528-0.

National-scale analysis of future river flow and soil moisture droughts: potential changes in drought characteristics

A.C. Rudd[1], A.L. Kay[1] and V.A. Bell[1]

[1]Centre for Ecology & Hydrology, Wallingford, UK, OX10 8BB

Corresponding author: Alison Rudd (alirud@ceh.ac.uk)

ORCID Rudd: 0000-0001-5996-6115, Kay: 0000-0002-5526-1756, Bell: 0000-0002-0792-5650

Abstract

The potential impact of climate change on drought is of increasing concern, especially due to recent occurrences of major events across the globe. Here a national-scale grid-based hydrological model is used to investigate potential future changes in river flow and soil moisture droughts across Great Britain. The analysis uses ensembles of climate model data for four time periods (1930s, 1980s, 2030s and 2080s) under a "business-as-usual" (RCP8.5) emissions trajectory. The results show that the severity of droughts are projected to increase in the future. River flow droughts in south-eastern regions are projected to increase in peak intensity and lengthen slightly, whereas peak intensities are projected to decrease for much of the rest of Britain. Droughts with the largest spatial extent across Britain are projected to increase in area for both river flow and soil moisture. More extreme droughts than previously experienced could have a significant impact on the aquatic environment as well as the availability of water for industry, agriculture and public water supply. Regional to national-scale droughts could have implications for potential mitigation measures such as water transfer between regions. In turn this could lead to social and economic impacts, especially as there are also likely to be future increases in demand.

Keywords

Drought, Great Britain, Hydrology, Low Flow, River Flow, Soil Moisture

1 Introduction

Droughts are a natural hazard and a fundamental feature of the climate of many regions of the world (Wilhite 2000). River flow and soil moisture droughts arise due to changes in the water balance and, in many cases, the additional impact of anthropogenic water use. Globally there is currently conflicting evidence (Trenberth et al. 2014) as to whether droughts are changing (Sheffield et al. 2012; Dai 2013; Damberg and AghaKouchak 2014). However, it is clear that some regions have experienced exceptional, prolonged and severe droughts in recent years (e.g. Australia, van Dijk et al. 2013; California, Griffin and Anchukaitis 2014; the Greater Horn of Africa, Nicholson 2014 and South Africa, Muller 2017). The UK drought of 2010-2012 had significant environmental (stress to wildlife), agricultural (poor crop yields) and societal impacts (temporary use bans) (Kendon et al. 2013). Had the drought not been terminated by unprecedented rainfall in April 2012 (Parry et al. 2013), it could have had even greater impacts.

Global warming may affect droughts due to changes in precipitation and evaporation patterns. Previous studies have used drought indicators to investigate projected changes in drought occurrence under future warming scenarios both globally (Sheffield and Wood 2008; Orlowsky and Seneviratne 2013; Cook et al. 2014) and at regional scales (South Korea, Rhee and Cho 2016; Crete, Vrochidou et al. 2013; UK, Blenkinsop and Fowler 2007, and Burke et al. 2010). Blenkinsop and Fowler (2007) found that short-term summer drought is projected to increase in most UK water resource regions except Scotland and Northern Ireland. However, they found large uncertainties in projections. Burke et al. (2010) found an overall increase in drought occurrence however the spread was considerable, ranging from little change to a slight decrease, to a significant increase depending on drought index, ensemble member and also location within the UK. A recent study by Collet et al. (2018) showed that catchments experiencing future increases in both floods and droughts are projected to be mainly along the western coast of England and Wales and across north-eastern Scotland. However, in a study of historical observed data Hannaford (2015) found that overall there seems to be little evidence of any strong decrease in low flows in Britain since the 1960s.

However, local drought impacts will depend on the management of water resources on national and regional scales. Droughts feature in the UK National Risk Register of Civil Emergencies (Cabinet Office 2017), and understanding how droughts might change in the future is key for managing drought risk and for water resource planning. In accordance with the Water Industry Act 1991, water companies in the UK are required to produce a Water Resource Management Plan that aims to balance water supplies and customer demand over a 25 year planning period. WaterUK (2016) states that potentially the best value option to address the supply/demand balance could be large-scale transfer of water between companies and regions. However, such options face significant technical, environmental and commercial challenges and schemes would need to be resilient under potential future climate change. The majority of UK water companies design supply systems to cope with the worst drought recorded in their area; when WaterUK (2016) was published, only two water companies had planned for resilience to droughts worse than those seen in the historic record. Regional Climate Model (RCM) simulations provide an opportunity to investigate potential future changes in water availability different to events that have occurred in the past. Many studies of historical and future GB droughts are based on analyses of precipitation, with no hydrological modelling (e.g. Rahiz and New 2013, Vidal and Wade 2009, Fowler and Kilsby 2004). This study addresses hydrological droughts, using large ensembles of river flow simulations generated from large ensembles of climate simulations. The use of large ensembles allows a greater range of plausible climates to be explored.

Rudd et al. (2017) examined historic droughts of Great Britain using a national-scale hydrological model, Grid-to-Grid (G2G), driven by observational data. They found substantial spatial and temporal variability in drought characteristics (severity, intensity and duration), but there were no consistent changes through time (1891-2015). This study applies some of the methods in Rudd et al. (2017) to quantify potential future changes in British droughts.

The study objectives are to:

(i) Analyse potential future changes in regional drought characteristics; and

(ii) Examine how the spatial extent of drought may change in the future.

Section 2 describes the hydrological model, the climate data, the drought identification method and the spatial analyses. Section 3 presents the results, Section 4 the Discussion, including a detailed discussion on sources of uncertainty, and Section 5 the Conclusions.

2 Methodology

2.1 Hydrological model

The Grid-to-Grid (G2G) is a national-scale rainfall-runoff model that provides estimates of natural river flows, runoff and soil moisture (in the unsaturated zone) on a 1km grid across Britain (Bell et al. 2009). It is parameterised using digital datasets (e.g. terrain and soil types) and operates on a 15-minute time-step. The G2G uses spatial datasets in preference to parameter identification via calibration, and where model parameters are required nationally-applicable values are used.

Model performance is good for a wide variety of catchments, particularly those with natural flow regimes as the model formulation does not currently account for artificial influences such as abstractions and discharges (Bell at al. 2009, Rudd et al. 2017). G2G is used operationally for forecasting fluvial flooding by the Flood Forecasting Centre for England and Wales and the Scottish Flood Forecasting Service (Cole and Moore 2009; Price et al. 2012; Maxey et al. 2012). The G2G has also been used to investigate the potential impact of climate change on flooding (Bell et al. 2012; Bell et al. 2016) and low flows (Kay et al. 2018).

Gridded time series of precipitation and potential evaporation (PE) are required to run the G2G model (Section 2.2). It can be configured with a snow module (Bell et al. 2016), but this is not used here for consistency with the low flow evaluation using historical data (Rudd et al. 2017), for which observed daily minimum and maximum temperature data needed as input to the snow module were not available. It is likely however that the effect of snowmelt on drought in Britain would be limited as flow regimes are dominated by rainfall in the vast majority of the country and snow is likely to be even less influential under projected warmer temperatures in the future (Kay 2016).

2.2 Driving data (climate model simulations)

The UK Climate Projections (UKCP09, Murphy et al. 2009) provided probabilistic climate change projections, and optional corresponding time series derived from a weather generator. While each method provides a large ensemble, neither provides spatially coherent data, so they cannot be used for national-scale analysis of droughts. Another potential source of climate data is CMIP5 (Taylor et al. 2012), which provides a multi-model ensemble of Global Climate Models (GCMs), but the limited number of simulations for each model means that they do not cover internal natural variability, and the resolution is relatively coarse. To address these shortcomings a new dataset was created to provide a large ensemble of spatially coherent high resolution climate time series, to capture the spatial variability and multivariate nature of droughts. The climate model data were produced as part of the MaRIUS project (Managing the Risks, Impacts and Uncertainties of drought and water Scarcity) using the weather@home2 system (Guillod et al. 2017a), which uses spare computing time on volunteers' computers to run large numbers of climate model simulations. The HadRM3P RCM is nested within an atmospheric GCM (HadAM3P) with prescribed sea surface temperatures (SSTs) and sea-ice conditions (Massey et al. 2015).

RCM data are available for three periods, Historical (1900-2006), Near-Future (2020-2049) and Far-Future (2070-2099), each consisting of 100 ensemble members (Guillod et al. 2017b). The individual ensemble members are generated by initial condition perturbations to the GCM to simulate the full range of internal variability that is possible with the model (Massey et al. 2015). To generate the individual ensemble members for each period, 13-month simulations (from 1 December) were stitched together using a novel technique based on identifying simulations with the best matching soil moisture patterns in the overlapping Decembers (Guillod et al. 2018). The Historical simulations have SSTs, sea-ice, greenhouse gas concentrations, SO_2 concentrations, volcanoes and solar activity prescribed to historical values. The future periods (Near-Future and Far-Future) are 30-year time-slices that correspond to the years 1975-2004 of the Historical simulation (Historical Baseline) but with added climate change. Therefore natural forcings (volcano and solar activity) are taken from 1975–2004 while greenhouse gases are taken from the RCP 8.5 emissions scenario (Riahi et al. 2011). For SSTs and sea-ice, the climate change signal derived from CMIP5 climate models is added to the Historical Baseline values. Five alternative Near-Future and Far-Future ensembles are available (Guillod et al. 2018), based on varying SST warming patterns; only the ensembles based on the median SST pattern are used here.

Due to seasonal biases in mean precipitation a bias-correction scheme based on monthly multiplicative factors was applied by Guillod et al. (2018). On average, future projections of precipitation show small increases in winter but large decreases in summer, leading to an overall drying. These projected changes are consistent with UKCP09 but larger in magnitude.

RCM PE was derived using the Penman-Monteith scheme (Monteith 1965), using monthly stomatal resistance (r_s) values as applied within the Met Office Rainfall and Evaporation Calculation Scheme (MORECS; Hough and Jones 1997) for the Historical time-slice but adjusting these values for the Near- and Far-Future time-slices, to allow for the closure of stomata under increased carbon dioxide concentrations (Rudd and Kay 2016; Guillod et al. 2018). PE is projected to increase in summer in the future, and to a lesser extent in autumn and spring, likely driven by increases in temperature (Guillod et al. 2018). However, adjusting r_s substantially reduces the projected future increases in PE, compared to use of fixed r_s values (Guillod et al. 2018).

Daily precipitation and PE data from each ensemble member of each period are used to drive G2G. The data are copied from the 0.22° (~25km) rotated latitude-longitude RCM grid to the corresponding $1km^2$ grid boxes of G2G, with additional weighting based on standard average annual rainfall patterns (1961-1990) for precipitation (Bell et al. 2007), and divided equally over each 15 minute model time step. Note that the RCM assumes 360-day years.

Four 30-year time-slices, each separated by 20 years, are considered in the subsequent analyses; Early-Historical (1920-1949), Recent-Historical (1970-1999), Near-Future (2020-2049) and Far-Future (2070-2099). The analyses are actually applied to 28-year time-slices, neglecting the first two years to allow for hydrological model spin up (Rudd et al. 2017).

2.3 Drought identification

Droughts are identified using the threshold level method (Yevjevich 1967; Hisdal et al. 2004) with the standardisation method of Rudd et al. (2017). This procedure is applied to time series of G2G-simulated monthly mean river flow (m^3s^{-1}) and soil moisture (mm water / m soil) to identify droughts, and their characteristics, at each 1km^2 grid box across Great Britain. The process can be summarised as follows:

Step 1: Remove the long-term monthly mean (1975-2004), X_{mon}, from the monthly mean time series, X, thus removing the seasonality;

$$\text{anomaly} = X - X_{mon}.$$

Step 2: Standardise the anomaly by dividing by the long-term monthly standard deviation (1975-2004), σ_{mon}, thus allowing comparison between different locations;

$$\text{standardised anomaly} = (X - X_{mon})/\sigma_{mon}.$$

Step 3: Calculate the duration, intensity and severity of the standardised deficits (negative anomalies)

i. standardised drought intensity — the deficit;
ii. drought duration — the length of time in deficit; and
iii. standardised drought severity — duration multiplied by mean standardised drought intensity.

Following Rudd et al. (2017) severity thresholds have been used to classify the simulated droughts as major or moderate, thus removing small (and likely low impact) droughts from subsequent analyses. The drought severity thresholds for river flow are 4 and 8, for moderate and major droughts respectively. The soil moisture thresholds are 8 and 16. Note that these thresholds were derived using an observation-driven G2G run, and their selection was somewhat subjective, based on a comparison of simulated droughts with observed (historically recorded) droughts, whose classification as major/moderate is also somewhat subjective (Rudd et al. 2017). This needs to be borne in mind when interpreting the results.

2.4 Regional drought characteristics

To examine potential future changes in the spatial and temporal nature of river flow and soil moisture droughts across Britain, the characteristics of all simulated drought events with severity exceeding the moderate-threshold, with duration longer than one month, were assessed for every 1km^2 grid box. Time-slice (28-year) mean values were calculated for each characteristic, for each ensemble member within the two historical and two future time-slices, and summarised for 19 river basin regions (Figure 2). Changes in mean intensity can be inferred from changes in severity and duration, however peak intensity cannot. Therefore in this study peak intensity (largest deficit) is used and hereafter “intensity” refers to the peak intensity across a drought event. Results are presented in Section 3.1.

2.5 Spatial extent of droughts

2.5.1 Coverage and seasonality of the largest extent droughts

To understand how the spatial extent of droughts might change in the future, the gridded monthly time series of standardised drought severity are analysed, for each of the 100 ensemble members in each of the four time-slices. For each month, the number of grid boxes with severity greater than or equal to the severity thresholds (Section 2.3) is counted to estimate the drought extent across Britain, and the month with the highest count is selected (using all grid boxes for soil moisture drought, but only those with a catchment area of at least 50km^2 for river flow drought). This will not necessarily be the most severe or intense drought in each grid box, but it will be the one that affects the largest area at one time. The variability in the largest drought extent per time-slice for all 100 ensemble members was analysed, as was the seasonality (month of occurrence) of the largest drought and the probability of the largest drought affecting a particular location (1km^2 grid box) (Section 3.2).

2.5.2 Coincident droughts in the Severn and Thames regions

New water transfer schemes between regions are being explored to reduce the pressure on supplies from an increasing population (WaterUK 2016). In particular, Thames Water Utilities Ltd are considering a water transfer scheme from the River Severn to safeguard supplies in the River Thames (TWUL 2017). A fundamental consideration of whether such a scheme could work would be whether the regions are affected by drought concurrently, i.e. is there sufficient water in the River Severn when the River Thames requires it.

A case-study is developed investigating the likelihood of drought occurring in these adjacent regions, and how this might change in the future. Similar to Section 2.5.1 but for major-threshold droughts only, and considering the Thames region rather than Great Britain as a whole, simulated droughts with the largest spatial extent are identified. If for a particular ensemble member there are two events in the Thames region with the same extent, then the one with the largest extent in the Severn region is selected. For example, if two droughts in an ensemble member cover 90% of the Thames region, but the first event affects 60% of the Severn region and the second affects 65%, then the second event is selected. This is to identify droughts that could have the greatest effect on whether there is water available for a transfer from the Severn to the Thames.

For each of the largest droughts in the Thames region the number of ensemble members that simulate a drought in the Severn region at the same time for a given percentage of river affected are considered. This provides an estimate of the probability of both regions experiencing the largest major drought at the same time, and is repeated for each time-slice. Results are presented in Section 3.2.1.

3 Results

3.1 Regional drought characteristics

The boxplots in Figure 1 summarise the ranges of river flow drought characteristics for each of the 19 regions (Figure 2 top). All regions are projected to have greater severities in the future, however the range of severities is greatest for regions in the south and east. This variability could be from the ensemble spread, the intra-region variation or a combination of both. For the Near- and Far-Future the range of intensities is greatest for the Humber, Anglian, Thames and SE England regions. Southern and eastern regions are projected to have slightly longer droughts into the future, with the Anglian, Thames and SE England regions having the longest droughts on average and also the greatest range of durations (Figure 1). For all three characteristics (severity, intensity and duration) there is considerable variability in the maximum and minimum values across the regions. Projected changes in soil moisture drought characteristics are similar to those for flow droughts (Supplementary Figure 1).

Figure 2 shows the change in median drought severity and intensity for the Near- and Far-Future time-slices compared to the Recent-Historical time-slice, for each of the 19 river basin regions. For river flow drought severity and intensity the largest projected changes are in the south east of England. The potential range of changes across the regions for river flow drought severity is 1 to 15% for the Near-Future and 1 to 24% for the Far-Future (to nearest whole number). For the Thames region the median severity is projected to increase by 14% from the Recent-Historical to the Near-Future time-slice, and by 24% from the Recent-Historical to the Far-Future time-slice. The range of projected changes for intensity is from -3% to +4% for the Near-Future and -6% to +6% for the Far-Future. While south-eastern regions (e.g. SE England and Thames) are projected to have higher intensity droughts in the future, central regions (e.g. NE England, Humber, Northumbria) and West Wales are projected to have lower intensities. For the Thames region the median intensity is projected to increase by 4% from the Recent-Historical to the Near-Future time-slice and by 6% from the Recent-Historical to the Far-Future time-slice, but for NW England and Clyde the median intensity is projected to decrease by 3% from the Recent-Historical to the Near-Future time-slice and decrease by 6% from the Recent-Historical to the Far-Future time-slice.

For soil moisture the largest percentage changes in median severity are projected to be in southern England for the Far-Future. For example the SW England and Severn region median severity is projected to increase by 4% from the Recent-Historical to the Near-Future time-slice and by 12% from the Recent-Historical to the Far-Future time-slice. The range of percentage changes for soil moisture drought severity (Near-Future: 0 to 12%, Far-Future: 0 to 15%) is less than for river flow. However, the range of percentage changes for soil moisture drought intensity (Near-Future: -4% to +11%, Far-Future: -5% to 16%) is higher than for river flow (Figure 2).

3.2 Spatial extent of droughts

The boxplots in Figure 3 show the ensemble range of the area affected by the largest (moderate- or major-threshold) river flow and soil moisture droughts, for each time-slice. See Supplementary Figures 2 to 9 for maps of the percentage extent of the largest major-threshold drought in each of the 19 regions, for each of the 100 ensemble members.

For both river flow and soil moisture the spatial extent of droughts increases into the future (Figure 3). For river flow, the ensemble median of the area covered by the largest moderate-threshold drought is ~80% for the historical time-slices, and increases to ~85% for the Near-Future and ~95% for the Far-Future. For the more severe, major-threshold droughts, the coverage is ~40% for the historical time-slices and increases to ~50% for the Near-Future and ~60% for the Far-Future. For moderate-threshold river flow droughts the ensemble spread decreases into the future (i.e. more similarity between the ensemble members). However, for the major-threshold droughts the ensemble spread is similar across the time-slices. For soil moisture droughts, the patterns of change over time are similar to those for river flow droughts, although they start from a lower percentage coverage.

The well-documented 1976 drought, which was the most extensive drought in the Recent-Historical time-slice (1970-1999) within the observation-driven G2G run of Rudd et al. (2017), sits within the range of the ensemble of possible realisations for the Recent-Historical time-slice (Figure 3). For the moderate-threshold river flow drought extent the 1976 event is on the lower end of the distribution. The opposite is the case for the major-threshold extent, reaffirming the rare occurrence of such a drought in Britain. For soil-moisture the 1976 drought is well within the box for the moderate-threshold drought extent, and just above the interquartile range for the major-threshold drought extent.

Figure 4 shows the probability of each 1km^2 grid box being in the (non-contiguous) area covered by the largest major-threshold river flow or soil moisture drought in each time-slice. Specifically, it represents the percentage of ensemble members projecting a grid box will be in the largest major-threshold drought. The figures highlight grid boxes that are most likely to be affected by the largest extent drought, however not necessarily at the same time. The susceptible areas for both river flow and soil moisture droughts tend to be in the south and east. The total area of Britain most susceptible to both river flow and soil moisture droughts is projected to increase into the future, with northern and western areas increasingly likely to be affected. Supplementary Figure 10 (regional mean) shows that regions such as West Wales, Dee and NW England have a greater projected increase between the Near-Future and Far-Future time-slices. Conversely, regions such as the Highlands show small increases in the probability of being in the largest major-threshold drought across all four time-slices.

Figure 5 shows the ensemble distribution of the month of the largest river flow drought for each time-slice (seasonality). For moderate-threshold river flow droughts the historical time-slices show a similar distribution, fairly flat with a slightly elevated occurrence in October to December. However, in future time-slices, there is a clear shift to more of the largest extent droughts occurring from August to December, and fewer occurring earlier in the year. For major-threshold river flow droughts there is a shift from a fairly flat distribution with a small peak in late winter/early spring in the historical time-slices, to a peak in November and December in the Far-Future time-slice. The distributions for soil moisture are similar to those for river flow (Supplementary Figure 11).

3.2.1 Coincident droughts in the Severn and Thames regions

Table 1 shows the number of ensemble members projecting a major-threshold river flow drought in the Thames and Severn regions at the same time. Unsurprisingly, the probability increases into the future. For example, there is a 43% chance of the largest major-threshold drought affecting at least 60% of the rivers in each region during the Near-Future time-slice, increasing to 72% for the Far-Future.

4 Discussion

4.1 Regional drought characteristics

The results show considerable variability in drought characteristics across regions and between time-slices. This is due to a combination of spatial differences in the climate projections (Guillod et al. 2018) but also differences in hydrological response via differences in catchment characteristics. However, drought severity is projected to increase into the future. This is probably due to an overall drying and an increase in PE, likely driven by increases in temperature, especially in summer (Guillod et al. 2018). An increase in drought severity could lead to more serious direct drought impacts such as reduction of water supply for domestic use, reduction in energy supply, reduction/loss of agricultural production, and environmental impacts such as algal blooms, wildfires, and river and lake pollution (NHP, 2013). The actual impact is dependent on the vulnerability and preparedness to drought risk and procedures in place to mitigate risk during a drought. It should be noted that the analysis presented here does not take into account the increasing pressures on water supply from population growth or land use change.

While south-eastern regions are projected to have higher peak intensity droughts in the future, central regions are typically projected to have lower peak intensities. This is likely to be related to differences in the precipitation (and PE) changes simulated in different parts of the country (Guillod et al. 2018). Intensity changes could affect the river ecosystem, e.g. exceptionally low flows can affect the ability of aquatic organisms to recover from a drought. Southern and eastern regions are projected to have slightly longer droughts into the future compared to the historical time-slices, which could have an impact on the length of time that supply-side interventions (e.g. temporary use bans) need to be in place.

Rudd et al. (2017) found that over the period 1891-2015 groundwater-dependent areas (e.g. Thames, Anglian and SE England) typically experienced droughts of greater severity, which had longer durations rather than higher intensities. This study suggests that both characteristics will be a contributing factor in the future, as intensities are also projected to increase in these regions.

Projections for changes in drought characteristics could influence how water resource systems are managed in future. For example, the North West region relies heavily on lakes, reservoirs and rivers for public water supply; only about 8% comes from groundwater. Availability in surface water bodies can decrease quickly during periods of low rainfall and high water demand, which makes them vulnerable to drought. As a result the North West region currently implements management strategies over a shorter timescale than those regions that predominantly rely on groundwater (Environment Agency, 2013), but this might be less resilient if droughts in future are more severe.

For river flow drought severity and peak intensity the largest projected changes are in the south east of England, with decreases in intensity suggested in central regions. This is consistent with Rahiz and New (2013), who analysed drought intensity using monthly precipitation from the UKCP09 RCM ensemble and found that most regions in the south (e.g. SW and SE England, Severn and Thames) showed increases while other regions showed decreases (especially in the dry season). Also, considering a 6-month drought severity index derived from monthly precipitation, Fowler and Kilsby (2004) found that future projections suggest drought severity will increase in most regions of the UK for the period 2070 to 2100, particularly in the south and east. This is important as it indicates enhanced drought stress in already water-stressed regions.

For soil moisture the largest changes are projected to be in southern England. More regions are projected to have greater increases in peak intensity for soil moisture than river flow. This might be because soil moisture is more directly and immediately responsive to changes in rainfall, whereas river flows spatially aggregate changes in the upstream catchment; Figure 3 of Van Loon (2015) illustrates that streamflow is more attenuated than soil moisture.

4.2 Spatial extent of droughts

The total area of Britain most susceptible to major-threshold river flow and soil moisture droughts is projected to increase into the future, with northern and western areas increasingly likely to be affected. Western regions show a larger projected increase in probability of being within the area covered by the largest drought into the Far-Future. The patterns are similar for the largest river flow and soil moisture droughts, however soil moisture droughts tend to affect a smaller proportion of the total area. This could have implications on the management of water in most regions of Britain: if more of the country is affected by drought at the same time then this will limit the usefulness of water sharing/transfer schemes. From a water resource management perspective a small localised drought may be mitigated by moving water around within a water utility company, however if a drought affects a whole region like the south east of England then it is a more significant problem.

Until recently the majority of water companies designed supply systems to be resilient to the worse drought recorded in their region (WaterUK 2016). Now, an increasing number of companies are turning to stochastic or ensemble based projections to explore a larger range of future climates. The climate simulations (Guillod et al. 2017b) and subsequent hydrological simulations (Bell et al. 2018a, b) from this study are generated by initial condition perturbations and they provide a large set of possible realisations (simulating the range of internal variability) of past and future climates. Considering internal climate variability has been shown to be important for drought assessment (Gu et al. 2019). The availability of these datasets creates an opportunity for water companies to test their resilience to a larger range of potential droughts. As an example, for the Thames the 1976 water year (October 1975 - September 1976) was the most severe recent drought for which good records are available (TWUL 2013). The 1976 drought extent is within the bounds of the spatial extent of droughts modelled using the historical ensemble, and the future ensembles provide droughts of larger extent than that observed in 1976.

For the largest river flow drought, the seasonality is projected to change from a fairly flat distribution (i.e. similar likelihood of occurring at any time of year), to a greater likelihood of occurring from August to December (moderate-threshold) and November to December (major-threshold), and lower likelihood of occurring earlier in the year. Projected decreases in summer precipitation (and, in some areas, decreases in autumn precipitation) and increases in PE are likely to lead to greater accumulation of soil moisture deficits that can last longer into autumn/winter.

4.3 Sources of uncertainty

As with all drought identification, the results are influenced by the methods used to obtain them. In this study there is a dependence on the choice of the long-term mean threshold used in the threshold level method to determine when there is a deficit/drought, and on the severity thresholds used to restrict subsequent analyses. Alternative thresholds than the long term mean would generate different characteristics (e.g. a lower threshold would by definition identify fewer droughts, of shorter duration, lower intensity and lesser severity, Oosterwijk et al. 2009), and the severity thresholds would need to be adjusted accordingly. Although the relationship between the characteristics would be unlikely to change (Van Loon and Van Lanen 2012), it is unclear how changes in characteristics between time-slices would be affected.

A stationary threshold was used in this study, however it could be extended using the method of Wanders et al. (2015) who proposed a non-stationary approach to calculating the threshold for drought identification. Their transient variable threshold (VTM_t) is based on the flow values for the previous 30 years. Therefore the VTM_t adjusts to gradual changes in the hydrological regime as it responds to climate change. The authors show that this has an effect on the projected changes in global area in drought, effectively reducing the projected increase by considering the substantial influence adaptation to an altered hydrological regime has on future hydrological drought characteristics. The method used here does not consider adaptation to climate change.

The results presented here for future changes in Great Britain include sea-surface temperature changes derived from a number of GCMs, but the climate model ensembles themselves only use a single GCM with a single nested RCM; results using other GCMs could be different. Blenkinsop and Fowler (2007) found an increase in intense short-term droughts and a decrease in longer duration droughts using monthly precipitation from the PRUDENCE ensemble of climate models, but acknowledged that projected changes in longer droughts were influenced by the driving GCMs and were highly uncertain. The climate dataset only considers one greenhouse gas concentration trajectory (RCP8.5) which represents a high scenario of future warming; other scenarios could give different projected changes in hydrological and soil moisture droughts. Similarly, only one hydrological model has been applied here. In a study of changes in Q90 for catchments across Europe larger than 1000km^2, Marx et al. (2018) state that uncertainty from GCMs is generally higher than that from hydrological models, but that the latter cannot be ignored.

Another source of uncertainty is the calculation of PE. Ahmadalipour et al. (2017) investigated future changes in meteorological and hydrological drought characteristics in a US catchment using CMIP5 models and the Precipitation Runoff Modelling System. The authors highlight the importance of temperature both in PE calculations and also via snowmelt. Their study may however have overestimated the effect from PE due to the use of the standard FAO-56 calculation. The formulation of PE included in this study includes changes in stomatal resistance r_s due to changing CO_2 concentrations, which has been shown to decrease the projected changes in PE in the future (Rudd and Kay 2016) and to moderate decreases in low flows (Kay et al. 2018).

The results presented here do not include the effect of snow on droughts. This is not likely to affect the vast majority of Great Britain, except for snowy winters such as 1946/47 or 1962/63 which are less likely to occur in the future (Kay 2016), but it could be more influential in countries with colder winters and greater propensity for snowfall. Van Loon and Van Lanen (2012) and Van Loon et al. (2015) developed a hydrological drought typology, summarising the underlying processes for each hydrological drought type (HDT) into those with precipitation controls, temperature controls or a combination of both; of the eight HDTs, snow (or ice) is a factor in five (Table 2 of Van Loon 2015). Although above-normal evapotranspiration can aggravate a drought event and prevent drought recovery it was not found to be the sole cause of hydrological drought.

Water managers need to know what is happening, or could happen in the future, to real river flows, so the fact that the hydrological model applied here produces hypothetical 'natural' flows (i.e. does not include artificial influences like abstractions and discharges) could be an issue. Ongoing work aims to enhance G2G by including surface and groundwater abstractions/discharges, enabling the potential impact of a range of water-use scenarios on drought to be explored.

5 Conclusions

This study used a high-resolution national-scale gridded hydrological model and a large ensemble of regional climate model data to investigate potential future changes in river flow and soil moisture drought characteristics (severity, peak intensity, duration and extent) across Great Britain. The use of a single hydrological model for the whole of Great Britain has allowed a spatially-consistent analysis of droughts to be undertaken, including preliminary analysis of the feasibility of mitigation measures such as inter-regional water transfer. The study has generated a dataset of simulated flows that can extend scenarios used to test water supply systems in a changing climate, and could help inform long-term planning for drought management.

The results show that the severity of droughts are projected to increase in the future. River flow droughts in south-eastern regions are projected to increase in peak intensity and lengthen slightly, whereas peak intensities are projected to decrease for much of the rest of Britain. Droughts with the largest spatial extent across Britain are projected to increase in area for both river flow and soil moisture. Studies in other parts of the world have also projected increases in drought duration, severity, spatial extent and/or occurrence of hydrological droughts (e.g. in Norway, Wong et al. 2011; subtropical and tropical regions, Touma et al. 2015; Europe, Roudier et al. 2016 and globally, Van Huijgevoort et al. 2014) and soil moisture droughts (e.g. Europe, Samaniego et al. 2018; India, Mishra et al. 2014), and this study adds to the literature about how droughts might change in the future by providing detailed analyses for Great Britain, based on large ensembles of climate model data. Van Lanen et al. (2016) argue that drought impacts are related to the hydrology rather than solely the weather, and that the characteristics of meteorological and hydrological droughts can be very different, therefore a hydrological perspective on droughts, such as provided here, is important.

Acknowledgements

This study is an outcome of MaRIUS: Managing the Risks, Impacts and Uncertainties of droughts and water Scarcity. Financial support was provided by the UK Natural Environment Research Council (NE/L010208/1) as part of the UK Drought and Water Scarcity programme. There are no real or perceived financial conflicts of interest for any author. The data are available from the Environmental Information Data Centre (eidc.ceh.ac.uk). The authors would like to thank the two anonymous reviewers for their comments, which have helped to greatly improve this manuscript.

Table Caption

Table 1 Number of ensemble members (out of 100) projecting a major-threshold river flow drought in the Severn and Thames regions (considering the largest major-threshold Thames drought).

Figure captions

Figure 1 River flow drought characteristics (a) severity, (b) intensity and (c) duration averaged for each ensemble member within each of the four time-slices, for 19 river-basin regions. The boxes show the interquartile range across each region (river grid boxes with catchment area ≥ 50km^2) and each of the 100 ensemble members for each time-slice, with the median shown by the thicker line within each box. The whiskers mark the 5th and 95th percentiles, and the dashes outside the whiskers show the minimum and maximum values.

Figure 2 Top: The 19 river-basin regions used in the drought characterisation. Bottom: Median drought characteristics as percentage change from the Recent-Historical time-slice: river flow and soil moisture.

Figure 3 Largest drought as percentage coverage of Britain (extent) for the four time-slices. The boxes show the interquartile range for each time-slice, with the median shown by the thicker line within each box. The whiskers mark the 5th and 95th percentiles, and the dashes outside the whiskers show the minimum and maximum values. The star is for the 1976 drought.

Figure 4 Probability of each grid box (catchment area ≥ 50km^2) being in the largest major-threshold river flow drought (top) and probability of each grid box being in the largest major-threshold soil moisture drought (bottom), for four time-slices.

Figure 5 Distribution of the month of the largest river flow drought for each time-slice.

References

Ahmadalipour A, Moradkhani H, Demirel MC (2017). A comparative assessment of projected meteorological and hydrological droughts: Elucidating the role of temperature. J. Hydrol., 785-797.

Bell VA, Rudd AC et al. (2018a). Grid-to-Grid model estimates of monthly mean flow and soil moisture for Great Britain: weather@home2 (climate model) driving data [MaRIUS-G2G-WAH2-monthly]. NERC Environmental Information Data Centre. https://doi.org/10.5285/3b90962e-6fc8-4251-853e-b9683e37f790

Bell VA, Kay AL et al. (2018b). The MaRIUS-G2G datasets: Grid-to-Grid model estimates of flow and soil moisture for Great Britain using observed and climate model driving data. Geosci. Data J. doi: 10.1002/gdj3.55.

Bell VA, Kay AL et al. (2016). An assessment of the possible impacts of climate change on snow and peak river flows across Britain. Clim. Chang., 136(3), 539–553.

Bell VA, Kay AL et al. (2012). How might climate change affect river flows across the Thames Basin? An area-wide analysis using the UKCP09 Regional Climate Model ensemble. J. Hydrol. 442–443, 89–104.

Bell VA, Kay AL et al. (2009). Use of soil data in a grid-based hydrological model to estimate spatial variation in changing flood risk across the UK. J. Hydrol., 377(3–4), 335–350.

Bell VA, Kay AL et al. (2007). Development of a high resolution grid-based river flow model for use with regional climate model output. Hydrol. Earth Syst. Sci, 11(1), 532-549.

Blenkinsop S, Fowler HJ (2007). Changes in drought frequency, severity and duration for the British Isles projected by the PRUDENCE regional climate models. J. Hydrol. 342, 50–71.

Burke EJ, Perry RHJ, Brown SJ (2010). An extreme value analysis of UK drought and projections of change in the future. J. Hydrol. 388, 131–143.

Cabinet Office (2017). National Risk Register Of Civil Emergencies, 2017 edition. Available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/644968/UK_National_Risk_Register_2017.pdf. Date accessed: February 2018.

Cole SJ, Moore RJ (2009). Distributed hydrological modelling using weather radar in gauged and ungauged basins. Adv. Water Res., 32(7), 1107-1120.

Collet L, Harrigan S, Prudhomme C, Formetta G and Beevers L (2018). Future hot-spots for hydro-hazards in Great Britain: a probabilistic assessment. Hydrol. Earth Syst. Sci., 22, 5387-5401.

Cook BI, Smerdon JE, Seager R, Coats S (2014). Global warming and 21st century drying. Clim. Dyn. 1–21.

Dai A (2013). Increasing drought under global warming in observations and models. Nat. Clim. Change 3, 52-58.

Damberg L, AghaKouchak A (2014). Global trends and patters of drought from space. Theor. Appl. Climatol. 117, 441-448.

Environment Agency (2013). Managing Drought in the North West. Available at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/315916/20132307_NW_drought_plan_revised.pdf. Date accessed: February 2018.

Fowler HJ, Kilsby CG (2004). Future increases in UK water resource drought projected by a regional climate model. Proceedings of the *BHS International Conference on Hydrology: Science & Practice for the 21st Century*, London, 12-16 July 2004.

Griffin D, Anchukaitis KJ (2014). How unusual is the 2012-2014 California drought? Geophys. Res. Lett. 41, 9017-9023.

Gu L, Chen J et al. (2019). The contribution of internal climate variability to climate change impacts on droughts. Sci. Total Environ. doi: 10.1016/j.scitotenv.2019.05.345.

Guillod BP, Jones RG et al. (2018). A large set of potential past, present and future hydro-meteorological time series for the UK. Hydrol. Earth Syst. Sci., 22(1), 611–634.

Guillod BP, Jones RG et al. (2017a). weather@home 2: validation of an improved global-regional climate modelling system. Geosci. Model Dev., 10, 1849–1872.

Guillod BP, Jones RG et al. (2017b): Managing the Risks, Impacts and Uncertainties of drought and water Scarcity (MaRIUS) project: Large set of potential past and future climate time series for the UK from the weather@home2 model. Centre for Environmental Data Analysis. doi:10.5285/0cea8d7aca57427fae92241348ae9b03.

Hisdal H, Tallaksen LM et al. (2004). Hydrological drought characteristics, in: Hydrological Drought: Processes and Estimation Method for Streamflow and Groundwater. pp. 139–198.

Hannaford (2015). Climate-driven changes in UK river flows: A review of the evidence. Progress in Physical Geography, 39(1), 29-48.

Hough M, Jones RJA (1997). The United Kingdom Meteorological Office rainfall and evaporation calculation system: MORECS version 2.0– an overview. Hydrol. Earth Syst. Sci., 1(2), 227–239.

Kay AL (2016). A review of snow in Britain: the historical picture and future projections. Prog. Phys. Geogr., 40(5), 676–698.

Kay AL, Bell VA et al. (2018). National-scale analysis of low flow frequency: historical trends and potential future changes. Clim. Chang., doi:10.1007/s10584-018-2145-y

Kendon M, Marsh T, Parry S. (2013). The 2010-2012 drought in England and Wales. Weather, Vol. 68, No. 4.

Marx A, Kumar R et al. (2018). Climate change alters low flows in Europe under global warming of 1.5, 2, and 3°C. Hydrol Earth Syst. Sci., 22(2), 1017-1032.

Massey N, Jones R et al. (2015). weather@home – development and validation of a very large ensemble modelling system for probabilistic event attribution, Quart. J. Roy. Meteor. Soc., 141, 1528–1545.

Maxey R, Cranston M et al. (2012). The use of deterministic and probabilistic forecasting in countrywide flood guidance in Scotland, in: BHS Eleventh National Symposium, Hydrology for a Changing World, pp.01–07.

Mishra V, Shah R, Thrasher B (2014). Soil Moisture Droughts under the Retrospective and Projected Climate in India. J. Hydrometeorol., 15, 2267-2292.

Monteith JL (1965). Evaporation and environment. Symp. Soc. Exp. Biol., 19, 205–234.

Muller M (2017). Understanding Cape Town's Water Crisis. Civil Engineering, June 2017. Available at SSRN: https://ssrn.com/abstract=2995937. Date accessed: February 2018.

Murphy JM, Sexton DMH et al. (2009). UK climate projections science report: climate change projections, Tech. rep., Met Office Hadley Centre, Exeter.

NHP, 2013. Drought, Natural Hazards Partnership Science Note: 2013.

Nicholson S (2014). A detailed look at the recent drought situation in the Greater Horn of Africa. J. Arid Environ., 103, 71-79.

Orlowsky B, Seneviratne SI (2013). Elusive drought: Uncertainty in observed trends and short-and long-term CMIP5 projections. Hydrol. Earth Syst. Sci. 17, 1765–1781.

Oosterwijk J, Van Loon AF et al. (2009) Hydrological drought characteristics of the Nedožery sub catchment, Upper Nitra, Slovakia, based on HBV modelling. WATCH Technical Report no. 20. http://www.eu-watch.org/nl/25222760-Technical_Reports.html.

Parry S, Marsh T, Kendon M (2013). 2012: from droughts to floods in England and Wales, Weather, Vol. 68, No. 10.

Peters E, Torfs PJJF et al. (2003). Propagation of drought through groundwater - A new approach using linear reservoir theory. Hydrol. Process. 17, 3023–3040.

Price D, Hudson K et al. (2012). Operational use of a grid-based model for flood forecasting, in: Proceedings of the ICE, Water Management, 65–77.

Rahiz M, New M (2013). 21st Century Drought Scenarios for the UK. Water Res. Man. 27, 1039-1061.

Rhee J, Cho J (2016). Future changes in drought characteristics: Regional analysis for South Korea under CMIP5 projections. J. Hydrometeorol., 17, 437-451.

Riahi K, Rao S et al. (2011). RCP 8.5—A scenario of comparatively high greenhouse gas emissions. Clim. Chang., 109, 33–57.

Roudier P, Andersson JCM et al. (2016). Projections of future floods and hydrological droughts in Europe under a +2°C global warming. Clim. Chang., 135, 341-355.

Rudd AC, Bell VA, Kay AL (2017). National-scale analysis of simulated hydrological droughts (1891–2015). J. Hydrol., 550. 368-385.

Rudd AC, Kay AL (2016). Use of very high resolution climate model data for hydrological modelling: estimation of potential evaporation. Hydrology Research, 47 (3), 660-670.

Samaniego L, Thober S et al. (2018). Anthropogenic warming exacerbates European soil moisture droughts. Nature Climate Change. 8, 421–426.

Sheffield J, Wood EF, Roderick M (2012). Little change in global drought over the past 60 years. Nature, 491, 435-438.

Sheffield J, Wood EF (2008). Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. Clim. Dyn, 31:79-105.

Taylor KE, Stouffer RJ, Meehl GA (2012). An Overview of CMIP5 and the Experiment Design. B. Am. Meteorol. Soc., 93, 485-498.

Touma D, Ashfaq M, Nayak MA, Kao S-C, Diffenbaugh NS (2015). A multi-model and multi-index evaluation of drought characteristics in the 21st century. J. Hydrol., 526, 196-207.

Trenberth KE, Dai A et al. (2014). Global warming and changes in drought. Nat. Clim. Change, 4, 17-22.

TWUL (2013). Thames Water Utilities Ltd MARCH 2013 FINAL DRAFT DROUGHT PLAN, APPENDIX F. Drought Management Protocols for London and SWOX with worked examples. https://corporate.thameswater.co.uk/-/media/Site-Content/Thames-Water/Corporate/AboutUs/Our-strategies-and-plans/Our-Drought-Plan/Current-Drought-Plan/Drought_PlanF.pdf. Date accessed: February 2018.

TWUL (2017). Thames Water Utilities Ltd. Reports - published technical reports and documents which have been produced to inform their Water Resource Management Plan 2019. https://www.thameswater.co.uk/sitecore/content/Corporate/Corporate/About-us/Our-strategies-and-plans/Water-resources/Document-library/Thames-Water-reports. Date accessed: February 2018.

Van Dijk AIJM, Beck HE et al. (2013). 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.

Van Huijgevoort MHJ, van Lanen HAJ et al. (2014). Identification of changes in hydrological drought characteristics from a multi-GCM driven ensemble constrained by observed discharge. J. Hydrol., 512, 421-434.

Van Lanen HAJ, Laaha G et al. (2016). Hydrology needed to manage droughts: the 2015 European case. Hydrol. Process. 30, 3097–3104.

Van Loon AF, Van Lanen HAJ (2012). A process-based typology of hydrological drought. Hydrol. Earth Syst. Sci, 16, 1915–1946.

Van Loon AF (2015). Hydrological drought explained. WIREs Water 2:359-392.

Van Loon AF, Ploum SW et al. (2015). Hydrological drought types in cold climates: quantitative analysis of causing factors and qualitative survey of impacts. Hydrol. Earth Syst. Sci, 19, 1993-2016.

Vidal J-P, Wade S (2009). A multimodel assessment of future climatological droughts in the United Kingdom. Int. J. Climatol. 29:2056-2071.

Vrochidou AEK, Tsanis IK et al. (2013). The impact of climate change on hydrometeorological droughts at a basin scale. J. Hydrol. 476, 290–301.

Wanders N, Wada Y, Van Lanen HAJ (2015). Global hydrological droughts in the 21st century under a changing hydrological regime. Earth Syst. Dyn. 6, 1–15.

WaterUK (2016). Water resources long term planning framework (2015-2065) Technical Report. https://www.water.org.uk/water-resources-long-term-planning-framework. Date accessed: February 2018.

Wilhite DA (2000). Drought as a Natural Hazard: Concepts and Definitions. Published in Drought: A Global Assessment, Vol. 1, editied by Donald, A. Wilhite, chap 1. pp3-18.

Wong WK, Beldring *S* et al. (2011). Climate Change Effects on Spatiotemporal Patterns of Hydroclimatological Summer Droughts in Norway. J. Hydrometeorol., 12, 1205-1220.

Yevjevich V., (1967). An objective approach to definitions and investigations of continental hydrologic droughts. Hydrol. Pap. 23.

Tables

Table 1 Number of ensemble members (out of 100) projecting a major-threshold river flow drought in the Severn and Thames regions (considering the largest major-threshold Thames drought).

Time-slice	Minimum % coverage of each region*			
	60%	70%	80%	90%
Early-Historical (1922-1949)	26	14	10	5
Recent-Historical (1972-1999)	25	19	13	7
Near-Future (2022-2049)	43	33	18	8
Far-Future (2072-2099)	72	57	46	30

*considering only river points with a catchment area ≥50km^2.

Figures

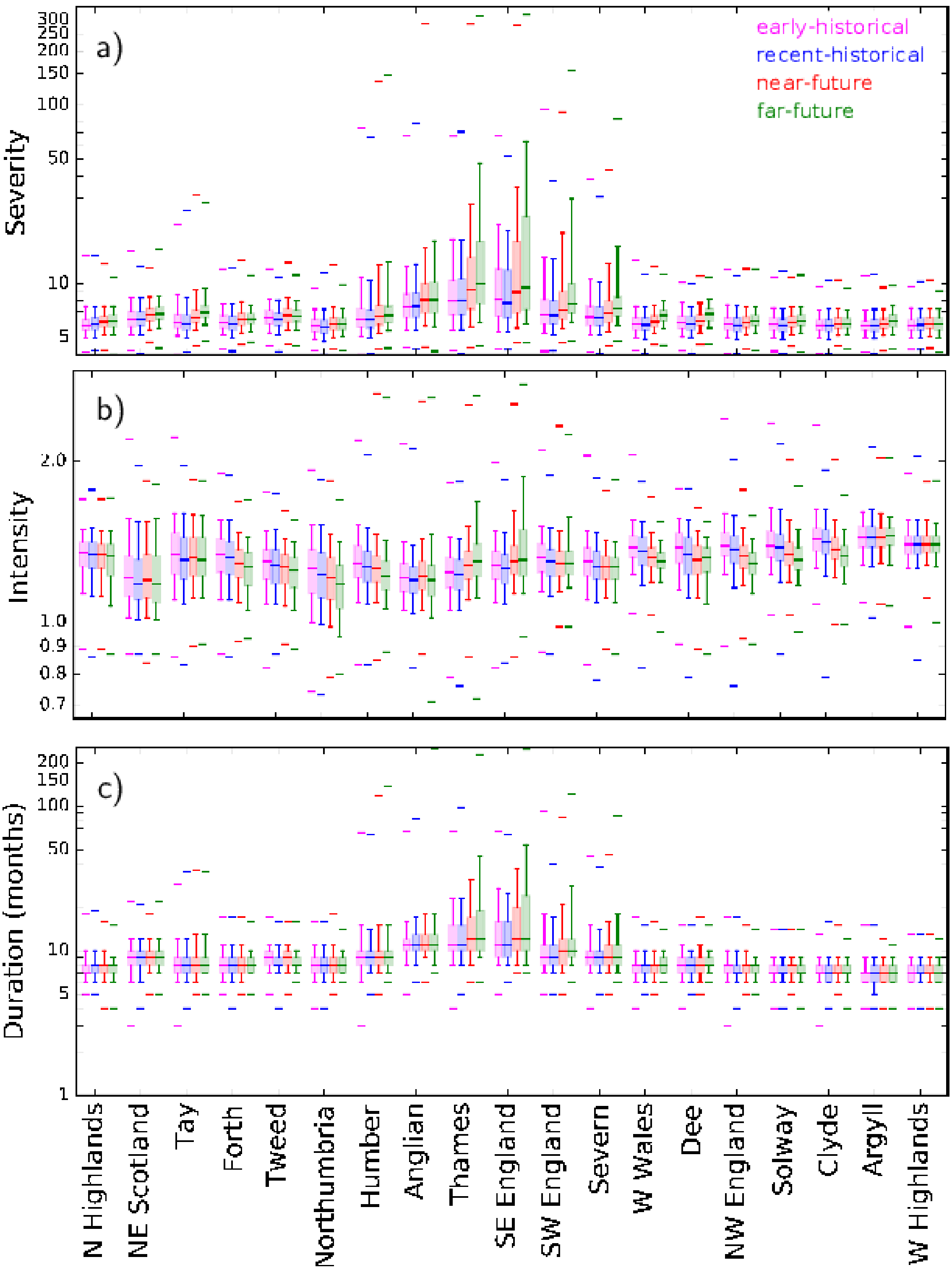

Figure 1 River flow drought characteristics (a) severity, (b) intensity and (c) duration averaged for each ensemble member within each of the four time-slices, for 19 river-basin regions. The boxes show the interquartile range across each region (river grid boxes with catchment area ≥ 50km^2) and each of the 100 ensemble members for each time-slice, with the median shown by the thicker line within each box. The whiskers mark the 5th and 95th percentiles, and the dashes outside the whiskers show the minimum and maximum values.

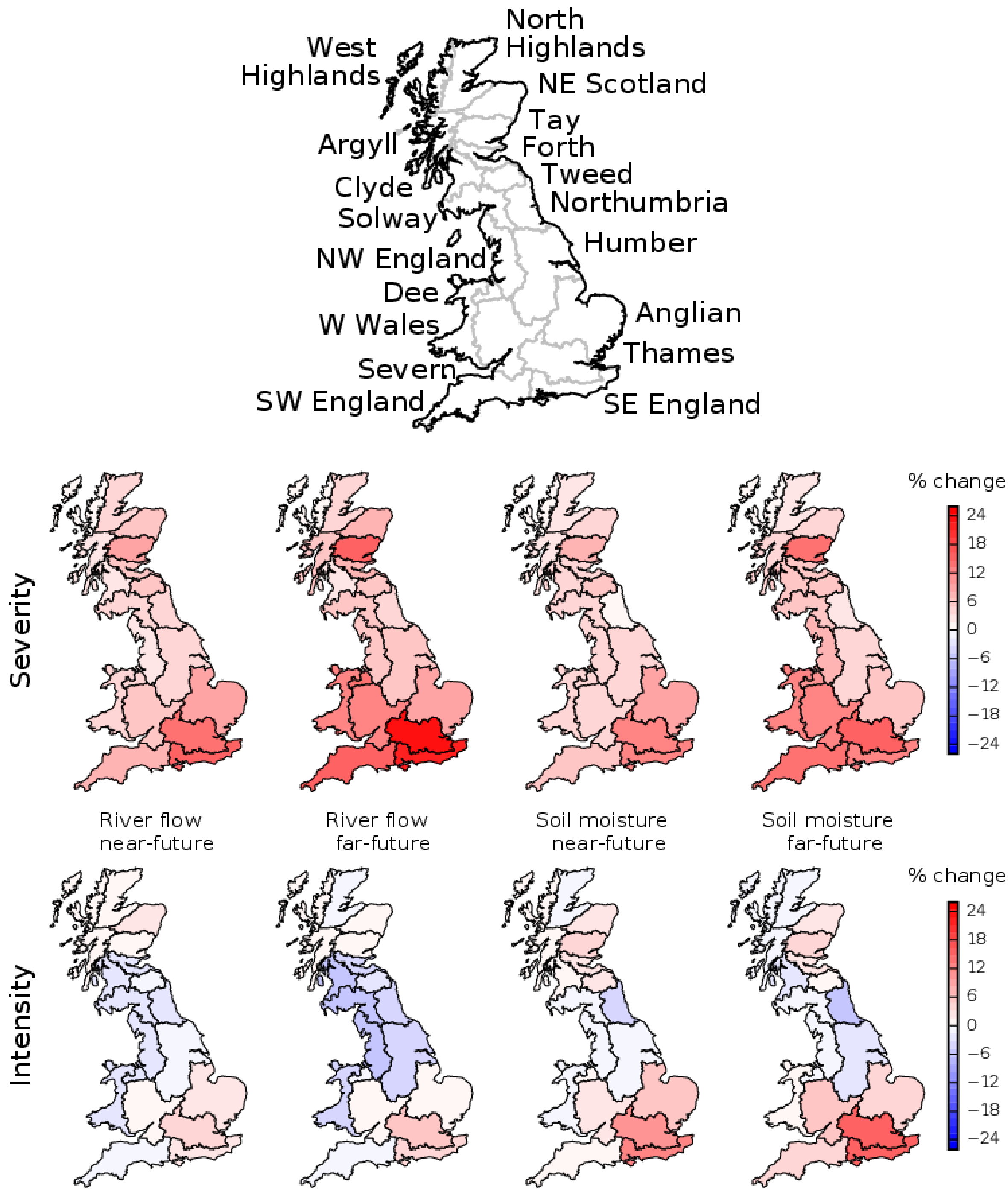

Figure 2 Top: The 19 river-basin regions used in the drought characterisation. Bottom: Median drought characteristics as percentage change from the Recent-Historical time-slice: river flow and soil moisture.

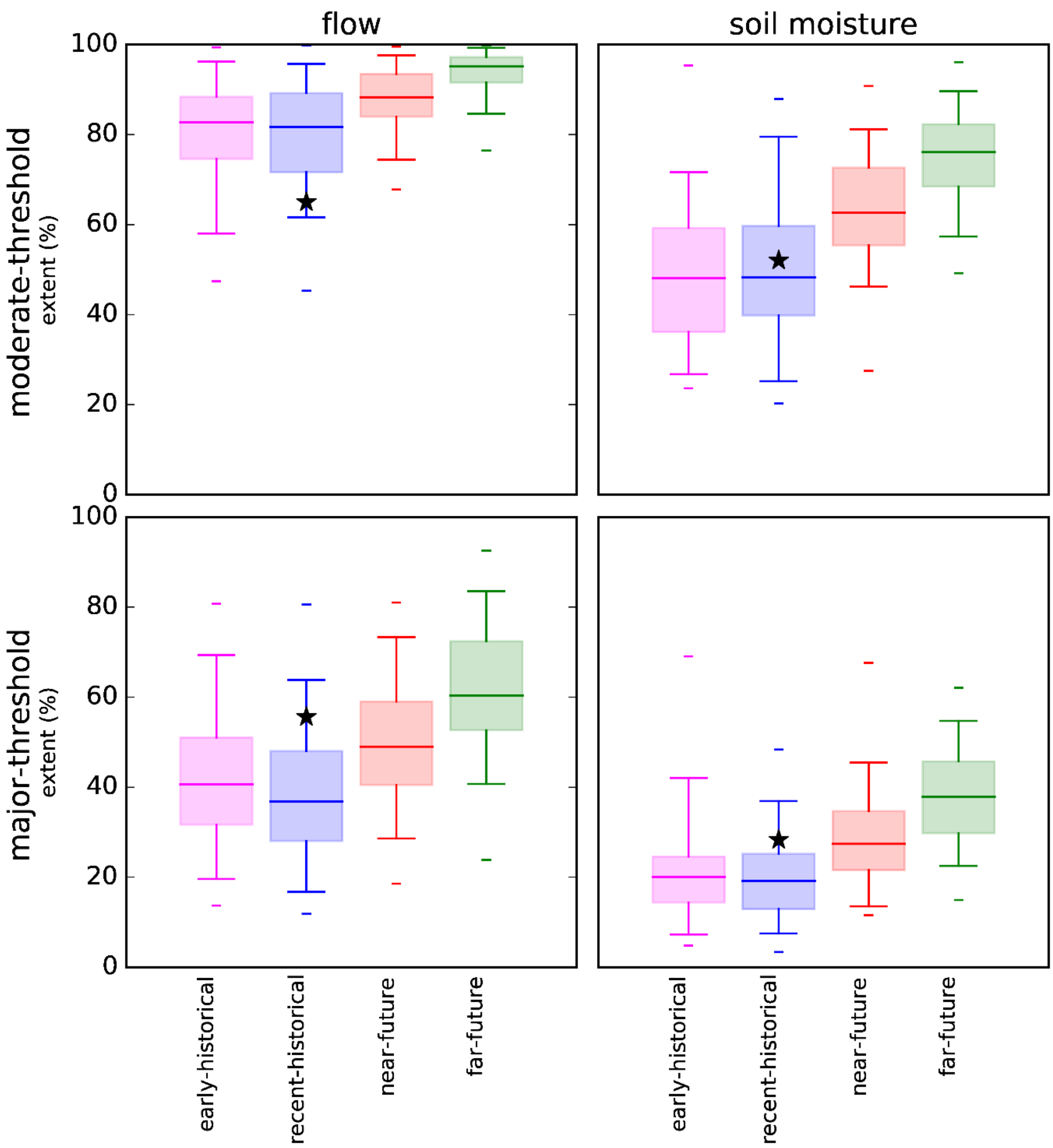

Figure 3 Largest drought as percentage coverage of Britain (extent) for the four time-slices. The boxes show the interquartile range for each time-slice, with the median shown by the thicker line within each box. The whiskers mark the 5th and 95th percentiles, and the dashes outside the whiskers show the minimum and maximum values. The star is for the 1976 drought.

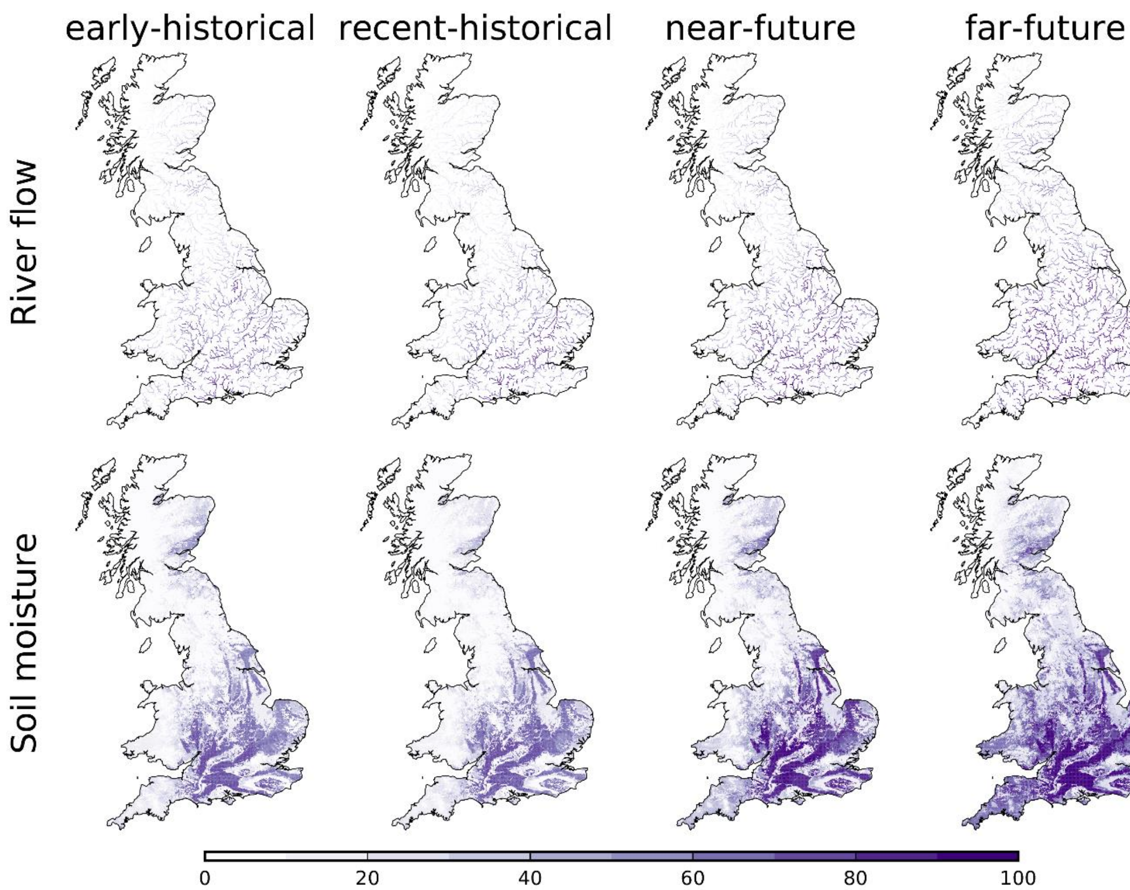

Figure 4 Probability of each grid box (catchment area ≥ 50km^2) being in the largest major-threshold river flow drought (top) and probability of each grid box being in the largest major-threshold soil moisture drought (bottom), for four time-slices.

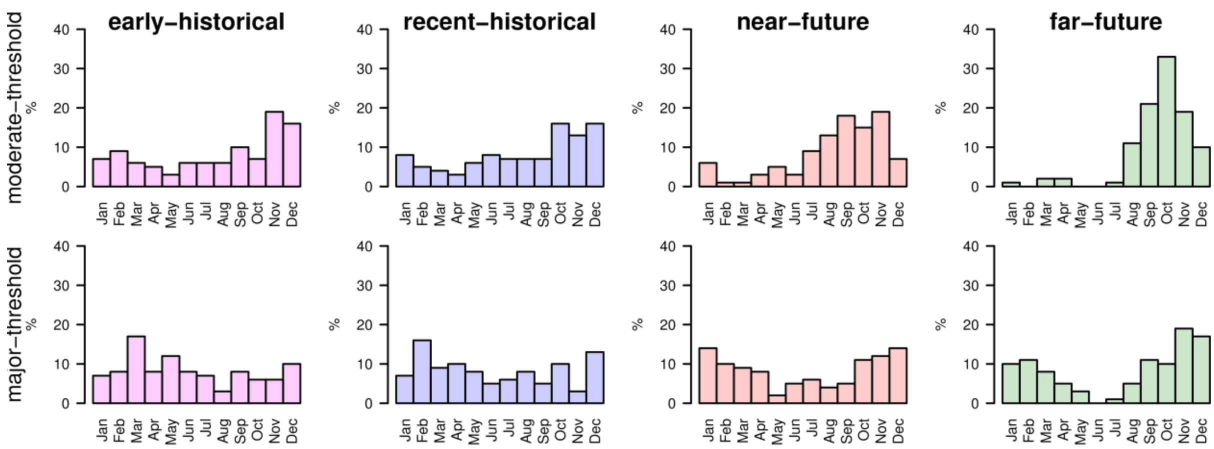

Figure 5 Distribution of the month of the largest river flow drought for each time-slice.

Supporting Information for

National-scale analysis of future river flow and soil moisture droughts: potential changes in drought characteristics

A.C. Rudd, A.L. Kay and V.A. Bell

Centre for Ecology & Hydrology, Wallingford, UK, OX10 8BB

Introduction

This supporting information provides additional figures, complementary to those in the main text. Included are

- Boxplots of soil moisture drought characteristics averaged over each of the four time-slices, for 19 river-basin regions (Figure S1);
- Maps showing the largest (major-threshold) drought as a percentage of the area of each of the 19 river basin regions, for each of the 100 ensemble members, for the four time-slices, for river flow (Figure S2-S5) and soil moisture (Figure S6-S9);
- Figure showing the probability of each grid box being in the largest major threshold river flow or soil moisture drought (Figure S10)
- Histograms showing the ensemble distribution of the month of the largest soil moisture drought for each time-slice (Figure S11).

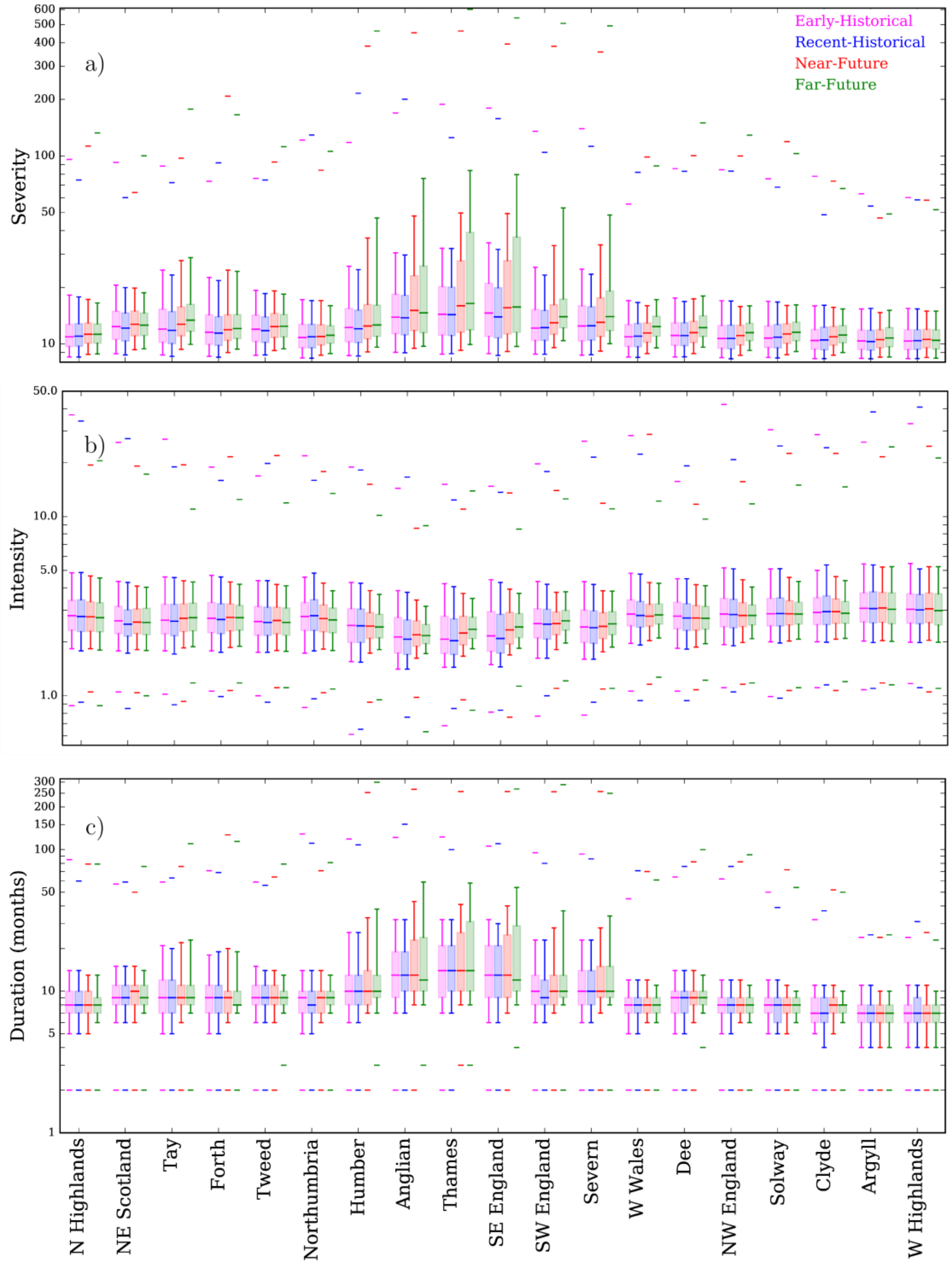

Figure S1. Soil moisture drought characteristics (a) severity, (b) intensity and (c) duration averaged for each ensemble member within each of the four time-slices, for 19 river-basin regions. The boxes show the interquartile range across each region (all grid boxes) and each of the 100 ensemble members for each time-slice, with the median shown by the thicker line within each box. The whiskers mark the 5th and 95th percentiles, and the dashes outside the whiskers show the minimum and maximum values.

Figure S2. Largest extent major-threshold river flow drought expressed as a percentage of the area of each region, for the 100 ensemble members (Early-Historical; 1922-1949).

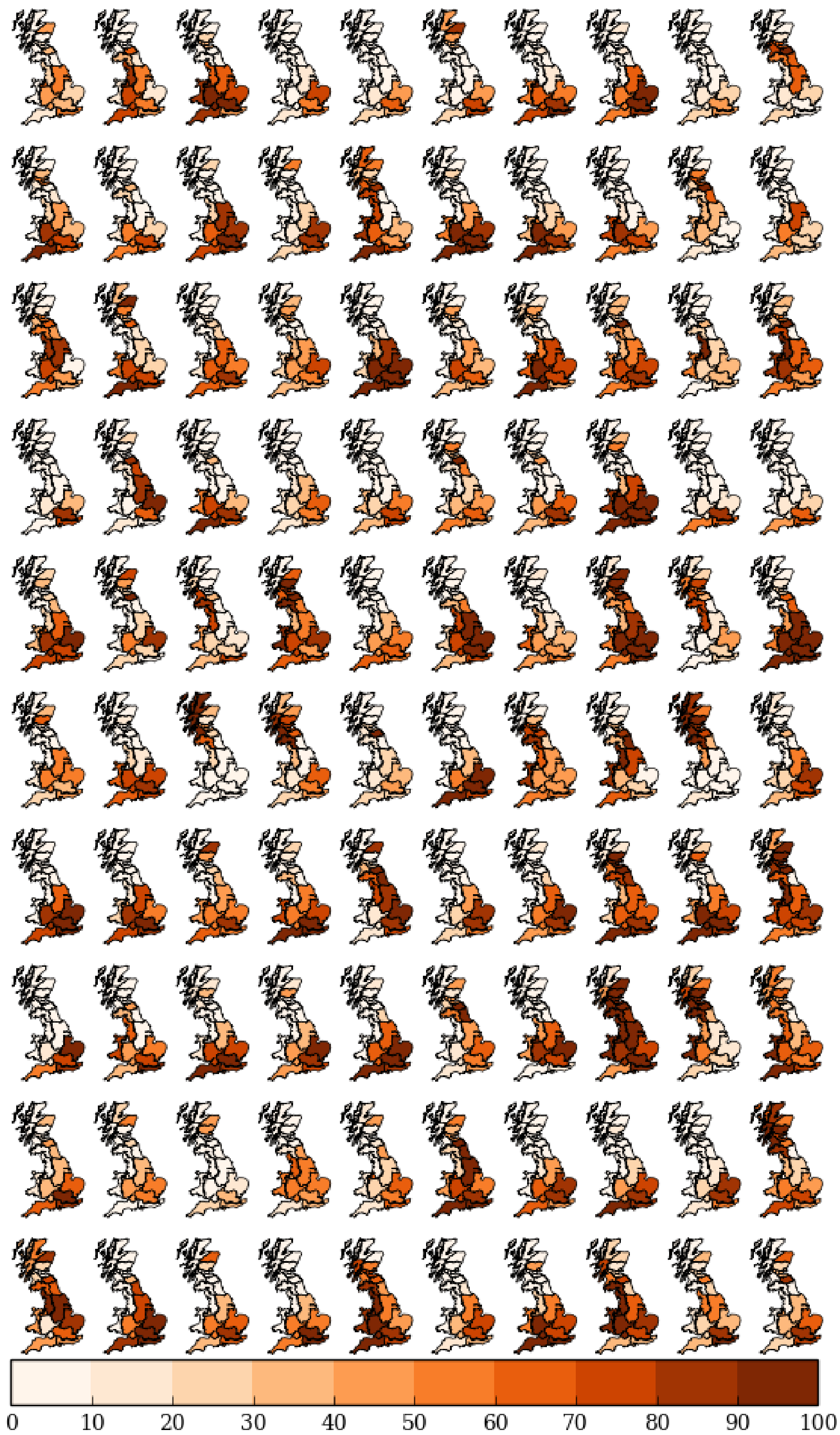

Figure S3. Largest extent major-threshold river flow drought expressed as a percentage of the area of each region, for the 100 ensemble members (Recent-Historical; 1972-1999).

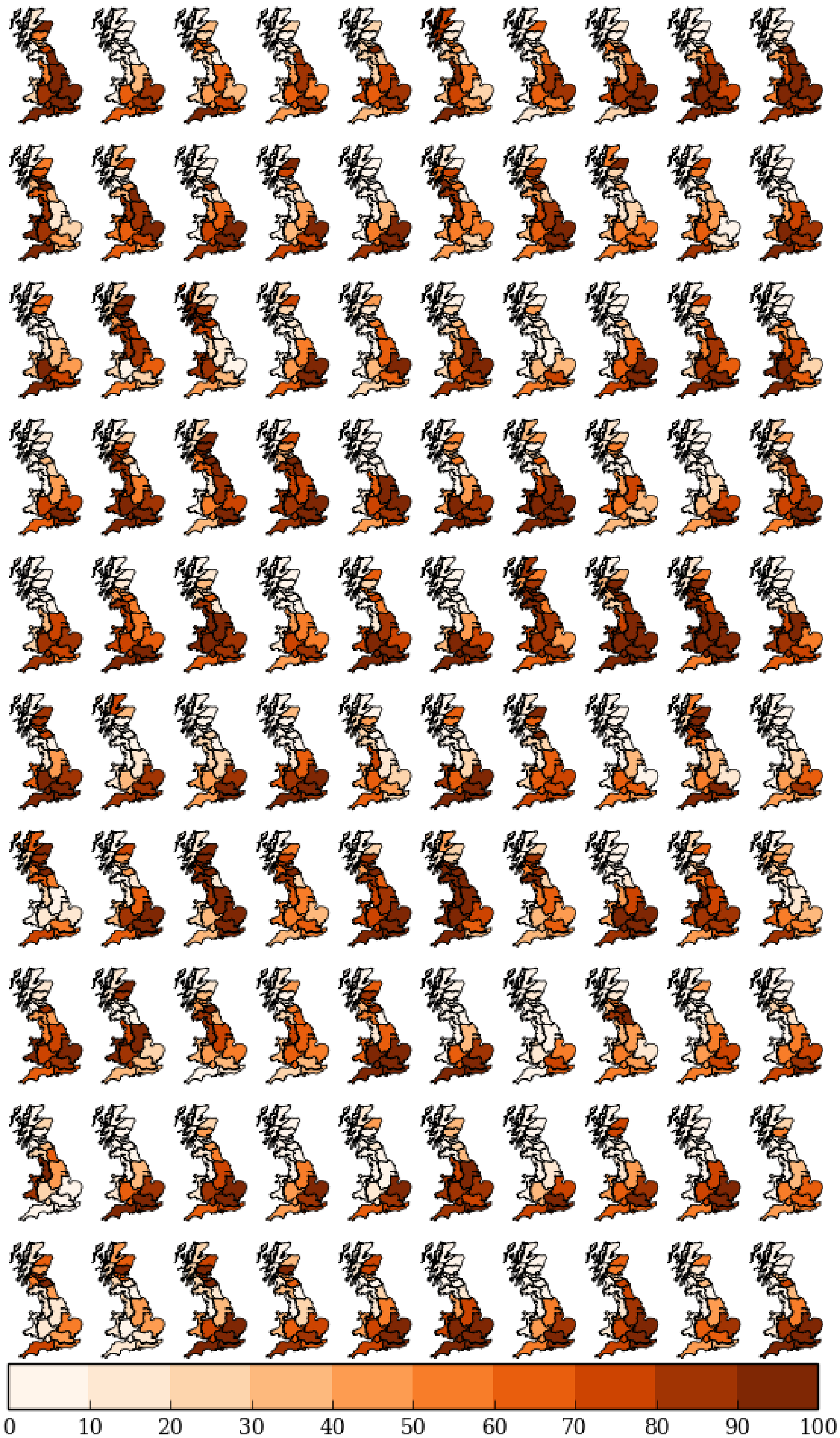

Figure S4. Largest extent major-threshold river flow drought expressed as a percentage of the area of each region, for the100 ensemble members (Near-Future; 2022-2049).

Figure S5. Largest extent major-threshold river flow drought expressed as a percentage of the area of each region, for the 100 ensemble members (Far-Future; 2072-2099).

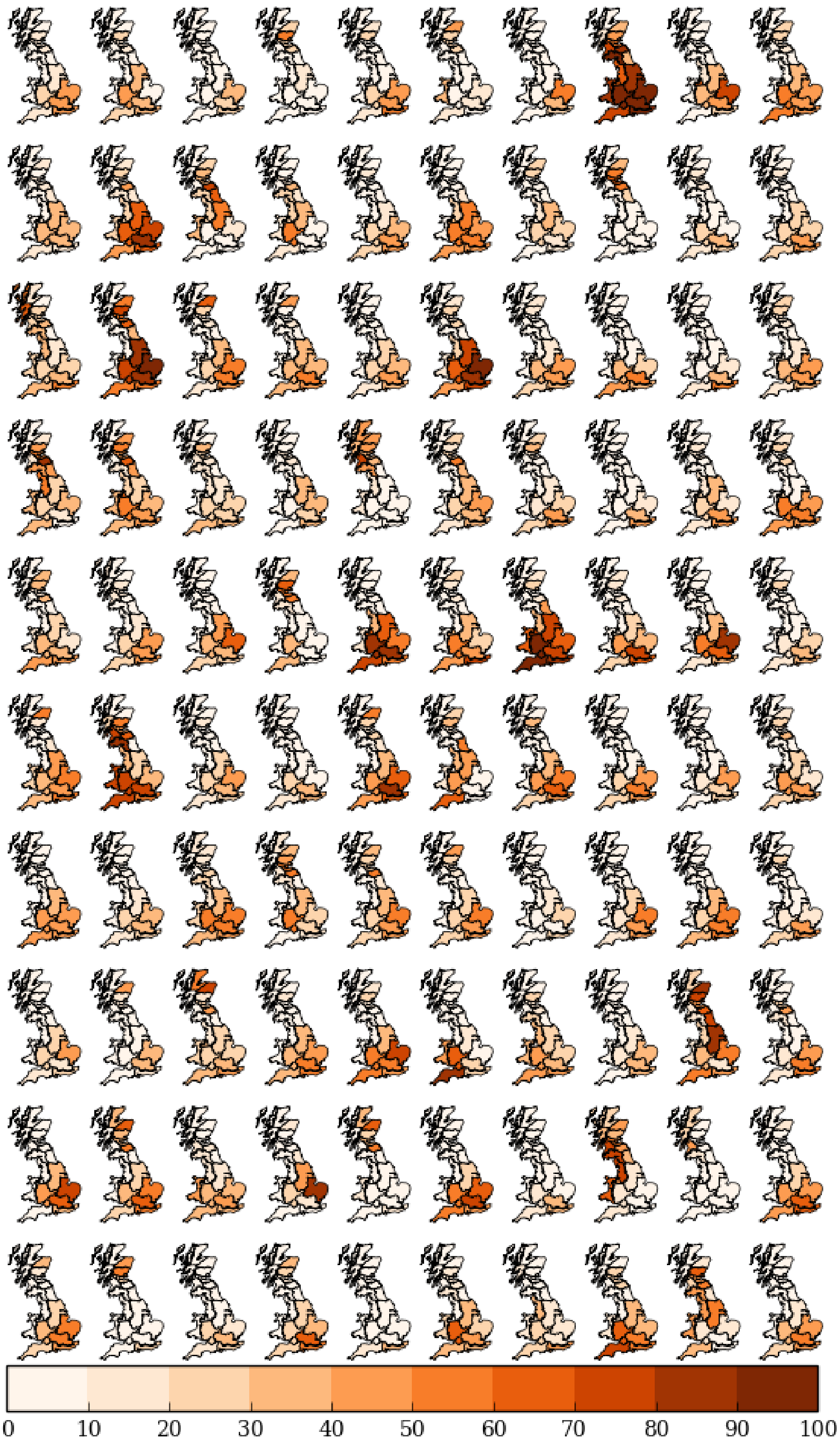

Figure S6. Largest extent major-threshold soil moisture drought expressed as a percentage of the area of each region, for the 100 ensemble members (Early-Historical; 1922-1949).

Figure S7. Largest extent major-threshold soil moisture drought expressed as a percentage of the area of each region, for the 100 ensemble members (Recent-Historical; 1972-1999).

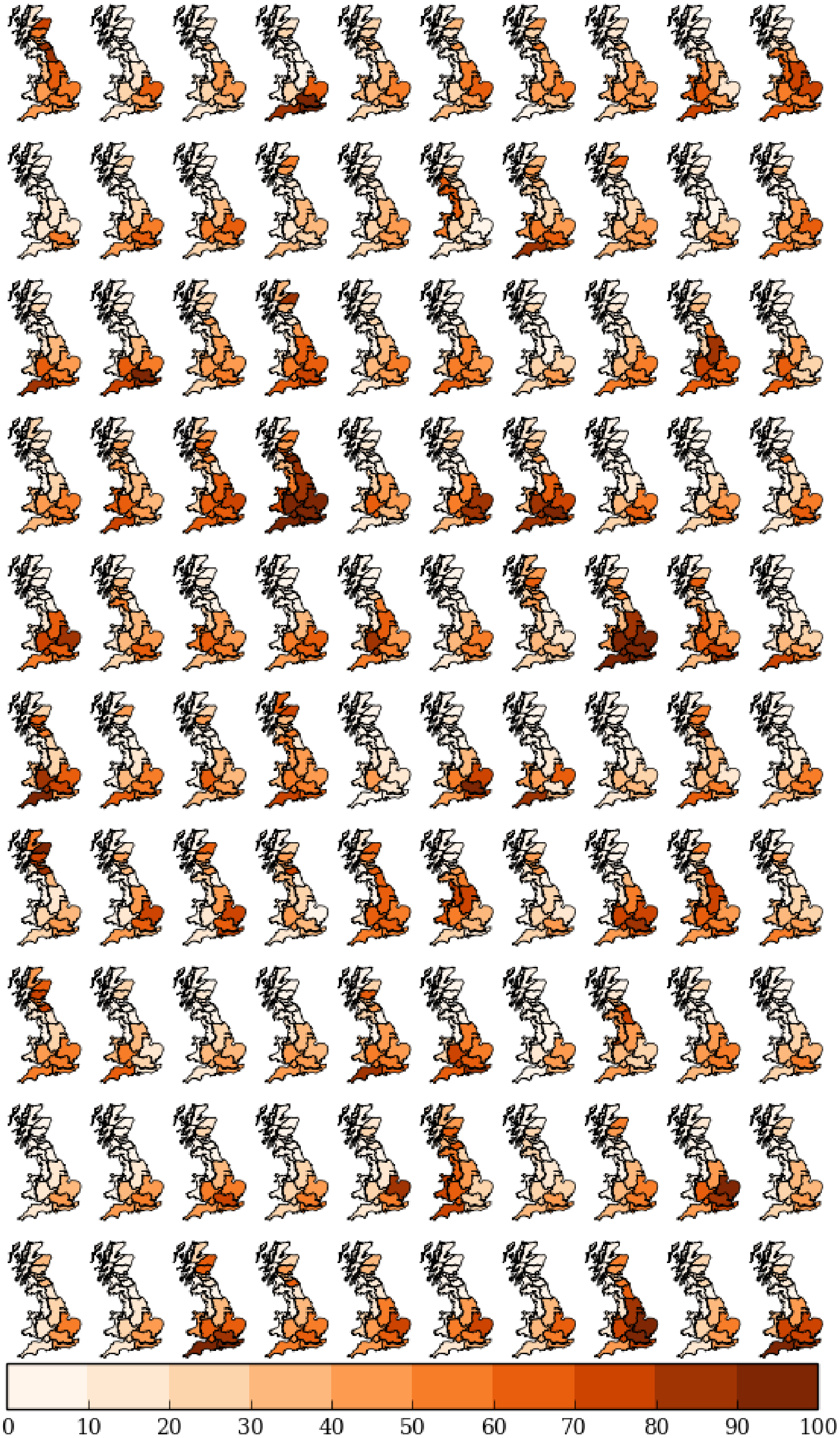

Figure S8. Largest extent major-threshold soil moisture drought expressed as a percentage of the area of each region, for the 100 ensemble members (Near-Future; 2022-2049).

Figure S9. Largest extent major-threshold soil moisture drought expressed as a percentage of the area of each region, for the 100 ensemble members (Far-Future; 2072-2099).

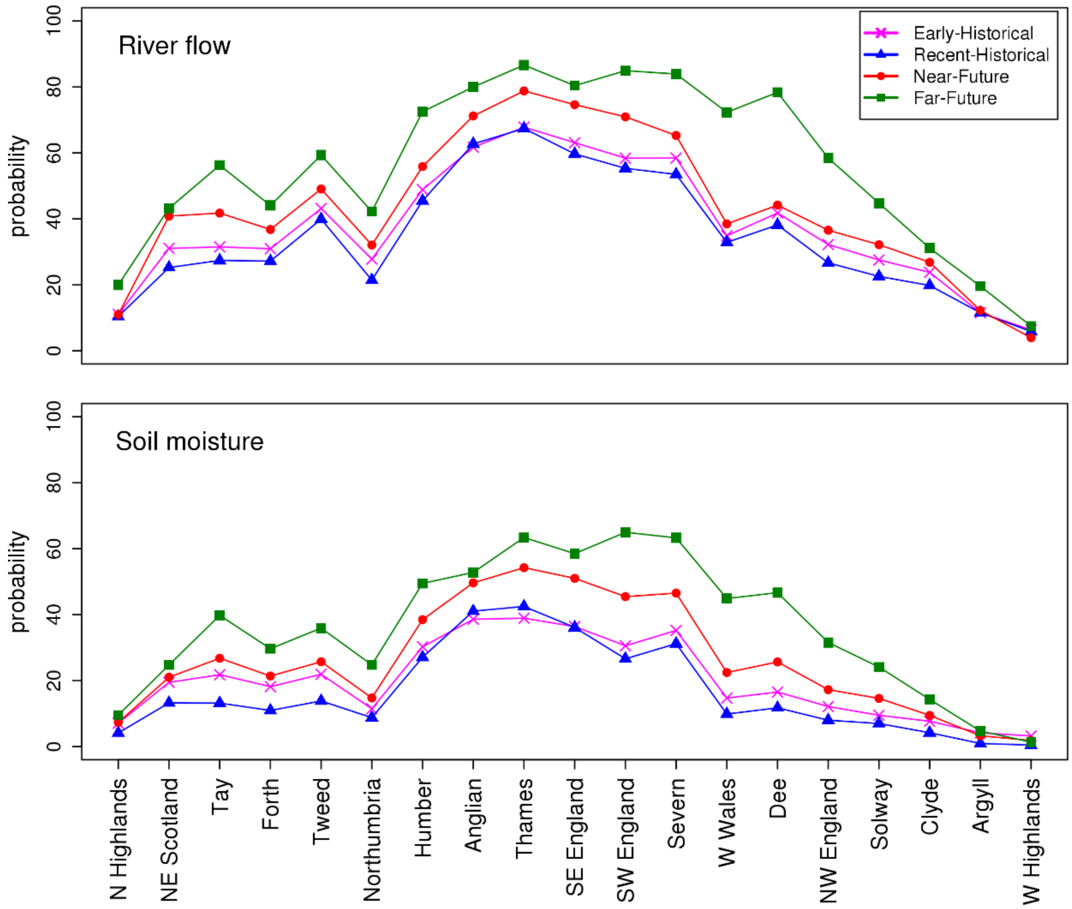

Figure S10. Probability of each grid box (catchment area ≥ 50km2) being in the largest major-threshold river flow drought (top) and probability of each grid box being in the largest major-threshold soil moisture drought (bottom), averaged over 19 river basin regions for four time-slices.

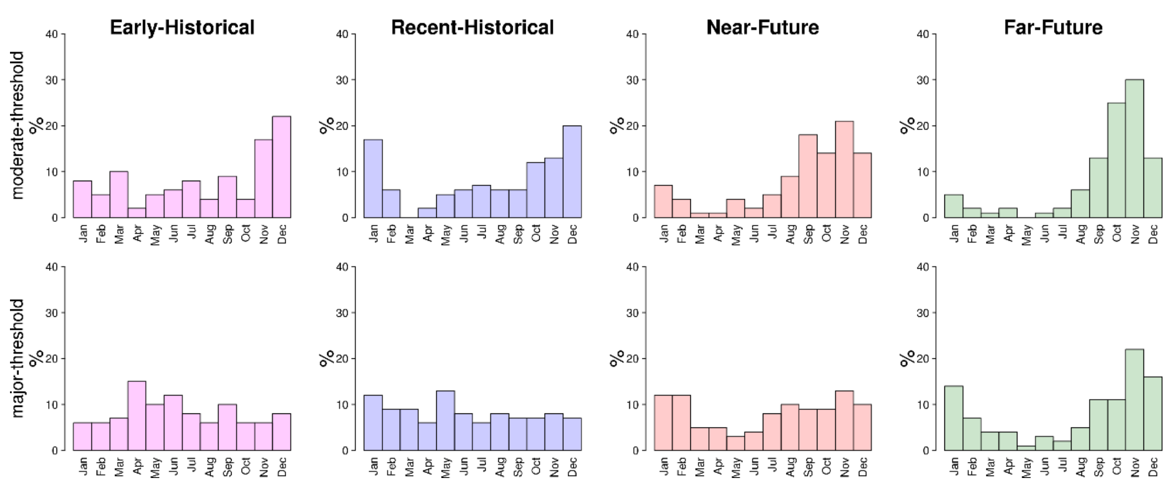

Figure S11. Distribution of the month of the largest soil moisture drought for each time-slice.