Droughts in Future Climate Change in the UK

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Abstract

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This thesis seeks to investigate the changes in the characteristics of 20th and 21st century meteorological droughts in the UK to address the following lines of inquiry: 1) *How credible are rainfall-based indices in representing hydrological droughts*, 2) *How coherent are droughts?*, 3) *Can alternative method of analysis provide new (or additional) information on the uncertainties in climate models?*, and 4) *Will future drought characteristics change?.* Key results, respectively, are summarized as follows:

- The drought severity index (DSI), can be considered a good proxy for assessing hydrological droughts as can be seen in its ability to capture the major hydrological events. The main caveat of the DSI is that there is often an underestimation of drought intensity and duration,
- Drought covariance is higher for the (i) wet season, (ii) moderate and (iii) shorter duration droughts,
- Evaluating climate models using drought statistics produces contrasting results compared with that using the model's precipitation fields. Drought statistics show biases which are largely negative, more intense, and have a greater spatial coverage.
- The projected ensemble-mean change is generally greater (and more widespread) for (i) moderate droughts and (ii) wet season compared with extreme droughts and the dry season, respectively with increases in drought intensity, drought covariance index, frequency of drought months and frequency of drought events for a given duration shown for England.

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The journey towards the doctoral degree at Oxford began on 11 January 2009. Approximately four years later, I am sitting behind my desk preparing to write this section, which typically marks the end of the journey. The effort put into the PhD was draining (I recall spending at least 10 hours in the lab especially in the first and second years) but definitely rewarding. I have gained a lot of knowledge, skills and experience throughout these years. Still, I do not consider myself an expert in the field yet. For now, I would proudly claim that I can get a task done well. Thanks are due to many for their support either for me or my work. Special mention needs to be conveyed to the following people:

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Chapter 1

Introduction

Studies have shown that extreme climatic events (*e.g.*, heatwaves, droughts, and floods) have become increasingly synonymous with a changing climate. According to the Special Report on Extremes (SREX) by the Intergovernmental Panel on Climate Change (IPCC), "*a changing climate leads to changes in the frequency, intensity, spatial extent, duration, and timing of weather and climate extremes, and can result in unprecedented extremes*" (IPCC, 2012). During the second half of the 20th century, weather-related events have caused significant damages in terms of lives and property (Beniston and Stephenson, 2004). Such incidents are consistent with the findings of the IPCC that extreme events are expected to heighten in a warmer climate (IPCC, 2007). It is important to understand the connection between climate change and extreme events because changes in the likelihood of the latter have direct impacts on every aspect of society's welfare, such as its economic well-being and physical comfort.

The IPCC SREX (2012) assigns medium confidence to the relationship between extreme events and anthropogenic climate change, referring to a 5-in-10 likelihood that observed changes in extreme events are caused by anthropogenic activities. The confidence level may reflect the lack of published studies on the topic. Nonetheless, event-based studies such as the 2000 UK floods (Pall *et al*., 2011), 2003 European heatwave (Stott *et al*., 2004), 2010 Russian heatwave

(Rahmstorf and Coumou, 2011; Otto *et al*., 2012) and the 2011 East African drought (Lott *et al*., 2013) show strong probability of attributable human-induced climate change.

Droughts are not only seen as an extreme event but also as a form of environmental disaster (Mishra and Singh, 2010) and have been a recurring feature of the climate in certain regions (Marsh *et al*., 2007; van Dijk *et al*., 2013). One of the world's leading reinsurance companies, Munich Re, calls droughts an "underestimated natural hazard" because their development are often unnoticed until they trigger famine (Munich Re, 2013). Studies have shown that droughts were common during the 20th century and evidence from global and regional climate models (GCMs and RCMs) has pointed to the increase in droughts in terms of their duration, spatial extent and/or trends over certain regions, such as the United States, UK, Europe and Australia, due to reduced precipitation and/or increased evaporation from increased temperatures which could potentially reduce the availability of water for the needs of society (Cai and Cowan, 2008; Dai, 2013).

Although the UK is traditionally thought of as a wet region, the disparity in the spatial distribution of seasonal rainfall, in addition to the changes in weather patterns and the growing demand for water arising from population growth, means that certain regions (*e.g.*, southeast England and Anglian) are more vulnerable to droughts. Recent decades have already seen a rise in the number of droughts in the UK, especially those relating to water resources with severe drought events now expected to occur every 10 years (Marsh, 2004). Future droughts in the UK have been projected to increase in frequency, duration and/or severity (*e.g.*, Fowler and Kilsby, 2004; Vidal and Wade, 2009; Burke *et al*., 2010). However, the uncertainties associated with these projections have meant that it is not possible to make robust assessments of future drought risks and their implications on water resources management, presenting both emerging challenge and opportunity for drought research (Rance *et al*., 2012)

1.1 Rationale and objectives

The core rationale for this research stems from the need to understand the influence of climate change on water resources so that better water resource planning and management practices can be implemented. Given that droughts are a recurring feature of the UK climate, the projected rise in temperature associated with future climate change can be expected to add pressure to water supply of a region and enhance the region's vulnerability to droughts, especially in already water-stressed areas, such as southeast England (Marsh *et al*., 1994; Arnell, 1998; Marsh *et al*., 2007; Dessai and Sims, 2010). Water resources management requires an understanding of the tools (*e.g.*, data and indices) used to detect droughts and their characteristics (*e.g.*, intensity, duration, and spatial distribution) which would influence the nature of the water resources management strategies. In light of these factors, this thesis sets out its research objectives as follows:

1. To assess the suitability of a rainfall-based drought index in representing hydrological droughts;

2. To examine the spatial coherence of droughts from the recent past;

3. To assess the reliability of the UKMO perturbed physics RCMs, used in the recent UKCP09, in their representation of drought characteristics; and

4. To examine the changes in 21st century drought characteristics in the UK projected by the UKMO RCMs.

1.2 Research contributions

Extensive work on droughts is available for the UK in the form of country-wide studies (*e.g.*, Vidal and Wade, 2009; Burke and Brown, 2010; Parry *et al*., 2012), regionally-focused analyses (*e.g.*, Philips and McGregor, 1998; Fowler and Kilsby, 2002a), event-based studies (*e.g.*, Walker and Smithers, 1998; Marsh, 2007), or as part of a wider European analysis (*e.g.*, Hisdal *et al*., 2001; Blenkinsop and Fowler, 2007a; Hannaford *et al*., 2011; Maule *et al*., 2013). The research in this thesis builds on this previous research and makes new contributions in the following ways:

- Elucidates on the suitability of utilizing a rainfall-based drought index to inform water resource planning and management;

- Introduces a new methodology to assess the spatial coherence of droughts;

- Presents an alternative approach of evaluating climate model's hydroclimatic characteristics through the measure of drought characteristics/statistics, rather than the commonly used method of analyzing biases in rainfall;

- Applies a drought index on a grid point-by-grid point basis over the whole of the UK, in contrast with most studies which focused on few locations or selected regions;

- Explores new drought characteristic in the form of frequency of drought events at a given duration (*FDD*), and presents detailed analysis of drought coherence and existing drought characteristics (*e.g.*, intensity and frequency);

- Analyses regional drought risk for each of the 23 water resource regions in the UK; and

- Uses a frequentist approach to analyse the 11-member perturbed-physics ensemble experiment dataset (HadRM3-PPE-UK) underlying the UK Climate Projections 2009 (UKCP09), compared with the probabilistic study by Burke and Brown (2010) and Burke *et al*. (2010).

1.3 Outline of thesis

The structure of the thesis follows the following organization: it begins with a review and a summary of existing literature on past and future droughts (Chapter 2). Caveats in existing research are identified in Chapter 3. The core research of this thesis is conveyed in Chapters 4-7. Chapter 4, "*Does a rainfall-based drought index simulate hydrological droughts*?" deals with the evaluation of the drought severity index (DSI) as a proxy for hydrological droughts. Chapter 5, "*Spatial coherence of meteorological droughts in the UK since 1914*", introduces a new method to assess the spatial coherence of historical droughts. In Chapter 6, "*Evaluation of the HadRM3-PPE-UK: Drought characteristics*", regional climate models are evaluated in terms of their ability to simulate observed drought characteristics. In Chapter 7, "*21st century drought scenarios for the UK*", drought characteristics in the HadRM3-PPE-UK for the 2030s, 2050s and 2080s are compared with those in the 1980s. Chapter 8 concludes the thesis with a summary of the key results and outlines directions from which future work can be carried out.

Chapter 2

Literature Review

2.1 Introduction

This chapter reviews the state of drought studies at global and regional scales. It forms the foundation from which gaps in research are identified (Chapter 3) and addressed in this thesis (Chapters 4-7). The review begins by addressing aspects of drought definition and issues associated with using indices to characterize droughts. The commonly known factors which influence droughts, such as temperature and atmospheric circulation, are detailed. Next, a general review of previous research on historical and future droughts are presented, focusing on several drought themes: time series of drought severity, extent of area and duration and/or frequency.

2.2 Drought Characterization

2.2.1 Definition

The study of droughts has been problematic. At the onset, researchers have to grapple with the most basic question of what a drought is. Although seemingly trivial, there has not been any universally accepted definition (Quiring, 2009; Mishra and Singh, 2010). The traditional definition embraces the notion of meteorology *i.e.*, precipitation deficit. However, such definition is limited as it does not address the effects of the deficit on social and biophysical systems. In response, a wide set of definitions bearing meteorological, hydrological, agricultural and socio-economic connotations has been introduced to suit the needs of respective researchers (Paulo and Pereira, 2006).

These definitions are subtle, but distinguishable (Heim, 2002; Marsh *et al*., 2007). Briefly, a meteorological drought results from the absence or lack of precipitation, compared to normal, over a prolonged period of time; an agricultural drought develops due to the unavailability of water at different stages of crop development to sustain production; a hydrological drought forms when water supply in storage systems, such as aquifers, reservoirs, and rivers, falls below the level required for their operational and/or ecological uses; and a socio-economic drought sets in when the shortage of water adversely affects the supply of an economic good or service (*e.g.*, hydroelectric power), or has an impact on the wider economy.

The propagation of meteorological droughts into hydrological droughts (and other forms) often shows an apparent lag effect. This has been shown in the case of the UK where hydrological droughts in the summer months are often associated with dry conditions of the preceding winter (Marsh *et al*., 2007). Catchment characteristics, such as geology, topography and land use, form a primary factor that controls the lag time between the onset of meteorological and hydrological droughts: flashy and slow-responding catchments are associated with shorter and longer lag times, respectively. This has important consequence on the vulnerability and the modulating ability of a region to drought events. In the context of the UK, regions characterized by groundwater reserves (*e.g.,* central and eastern England) have shown to be more vulnerable to droughts than those characterized by surface reservoirs (*e.g.*, northern and western upland regions) (Jones *et al*., 1997; Marsh *et al*., 2007).

Redmond (2002) suggested that a good definition is one which has the most universal range of applications. Oladipo (1985), for example, defined drought as a temporary event in which less than adequate precipitation occurs for a period of time. Other definitions adopt the same concept but with added emphasis on the disruption of activities or communities. Even such a general definition has proven problematic primarily because there is no consensus on what the duration of the sustained period of precipitation deficit is or how much deficit makes a drought event (Oladipo, 1985). Several criteria, specific to a given country or region, have been used. They include: 15 consecutive days with less than 0.25 mm of rainfall (Britain), deficit by more than two standard deviations (India), 10 days of total rainfall not exceeding 5 mm (Russia), six days without rain (Bali, Indonesia) (Heim, 2002).

The definition of drought based on length and quantity has little meaning from a water resources perspective since many hydrological drought events reflect stress on water supply for consumption, rather than rainfall deficit per se (Marsh *et al*., 2008). Although droughts are primarily precipitation-driven, the role of precipitation is not an exclusive factor as shortages in water supply in an area may also be triggered or exacerbated by factors such as over-abstraction of groundwater resources to meet the needs of population growth, land-use/land-cover changes and poor water management (Dai, 2011; van Dijk *et al*., 2013).

2.2.2 Quantifying droughts: Indices

The most common practice to studying droughts involves the use of indices which provides clear, simple and quantitative assessment of the major drought characteristics – intensity, duration and spatial extent (Wu *et al*., 2001; Heim, 2002). To date, many indices have been introduced and utilized. They include: Palmer Drought Severity Index (PDSI; Palmer, 1965), Standardized Precipitation Index (SPI; McKee *et al*., 1993), and Drought Severity Index (DSI; Phillips and McGregor, 1998), amongst others. A fundamental difference is that these indices are either rainfall-based or additionally factor in the soil-water balance. Other differences relate to the complexity of the index in terms of its computation and data requirements. Relatively simpler alternatives include the rainfall deficiency index, run analysis and the percentile method (Bonacci, 1993).

Drought indices are neither necessarily reliable nor consistent and no one index is superior over the other (Fowler and Kilsby, 2002a; Paulo and Pereira, 2006) (*see* Table 2.1 for a description of commonly used drought indices, and their merits and caveats). Such claims have been confirmed by research that evaluated the performance of different indices (*e.g.*, Oladipo, 1985 – Nebraska, United States; Agnew, 1989 – Niger; Wu *et al*., 2001 – China; Ntale and Gan, 2003 – East Africa; Morid *et al*., 2006 – Iran; Paulo and Pereira, 2006 – Portugal). In terms of drought identification/onset, responsiveness to rainfall events, spatial and temporal consistency, and usefulness for drought monitoring, some indices are comparable whereas others perform better (Oladipo, 1985; Wu *et al*., 2001; Morid *et al*., 2006).

Wu *et al*. (2001) evaluated the performance of SPI, the China-Z and z-score indices using data from four locations in China. They concluded that for very dry conditions, there was a large difference between the SPI and the China-Z, whereas the Z-score had a wet bias hence may not detect severe drought conditions. Oladipo (1985) recommended the Bhalme-Mooley index because it factored in month-to-month variation in precipitation although performance of the index was comparable with the PDSI and the rainfall anomaly index in detecting meteorological droughts in Nebraska. Paulo and Pereira (2006) applied the theory of runs, PDSI and SPI for local and regional drought studies in Portugal. The authors found difficulty in comparing the theory of runs with the SPI because the former required setting a critical rainfall threshold which, when varied, changed the duration of droughts. Although there was good agreement between the SPI and the PDSI with higher correlation at 12-month time scale, the authors suggested that the SPI had more advantage as it can be computed for more locations considering that only precipitation data were required, compared with the PDSI which required additional data (*e.g.*, soil moisture). Comparison between the PDSI and SPI was also performed by Lloyd-Hughes and Saunders (2002) who, in their study of 20th century European droughts, found that the PDSI was strongly correlated with the SPI at all time scales, with highest correlation at 9-12 months. There was greater consistency between the PDSI and SPI-12 in terms of simulating the mean frequency and duration of extreme and/or moderate droughts compared to other SPI time scales which showed either underestimation or overestimation.

In Taylor *et al.*'s (2013) comparison of four indices, the authors showed that the Soil Moisture Anomaly (SMA) and the PDSI simulated more significant increases in the drought duration whereas the SPI and the Standardized Runoff Index (SRI) showed significant decreases.

The SPI and the PDSI have been frequently used as a benchmark for evaluation of other indices. While the PDSI did give a good indication of drought (Khandekar, 2004), many studies recommended the use of the SPI. Ntale and Gan (2003) argued that the complexity of the PDSI involving multiple variables could be counter-productive. The authors compared the SPI with the PDSI and found that latter produced unrealistic results for drier locations in northern East Africa. The SPI was simple and provided more consistent results, enabling the authors to compare the output from different locations in study area. This aspect of spatial consistency was also verified by Wu *et al*. (2001). Unlike the PDSI which had a slower response time of 8-12 months, the SPI was responsive to precipitation deficits at a shorter time scale (*i.e.*, 3 months) and had the ability to monitor dry and wet periods over a wider temporal scale of 1-72 months (Wu *et al*., 2001). The greatest merit of the SPI was the very extensive and robust diagnosis of its properties involving close to 1200 stations in the United States before its formal introduction (Redmond, 2002).

One index which has been frequently used but has yet to be evaluated against other indices is the DSI. The DSI has been applied to assess regional drought risk in the UK (*e.g.*, Philips and McGregor, 1998; Fowler and Kilsby, 2002a, 2004; Blenkinsop and Fowler, 2007a, 2007b) and carries the following merits: 1) computationally less extensive compared with the PDSI, 2) requires no transformation of data (*e.g.*, fitting a distribution curve) compared with the SPI, and 3) flexibility of the index's termination rule (*e.g.*, 3- or 6-month) makes it possible to assess surface-water and/or water resource droughts. The DSI's termination rule can also be its limitation. As shown by Phillips and McGregor (1998), rule changes affect the initiation sequences, duration and severity of droughts detected. This could be misleading in that drought severities and durations can be underestimated or overestimated, depending on the termination rule specified in the algorithm. In addition, the assumption of the stationarity of evaporation rates suggests that droughts simulated by the DSI, as with other rainfall-based drought indices, may not reflect actual drought conditions (Blenkinsop and Fowler, 2007a).

Researchers are often faced with the question of which index (or indices) to apply to their area of study. Although SPI has more positive reviews, users should not be inclined to using a particular index based on its popularity. As a guide, several criteria have been proposed to identify a drought index suitable for a particular region. Keyantash and Dracup (2002) suggested several aspects for consideration: robustness, tractability, transparency, sophisticatedness, extendibility and dimensionality of the index. Ntale and Gan (2003) used the following eight criteria: 1) characteristics, statistical properties and variability of the index, 2) detailed analysis of a major historical drought, 3) adaptation of drought indices to local climate, 4) unbounded index values, 5) spatial invariability, 6) flexible time scale, 7) data requirement and availability and 8) interpretability. Bonacci (1993) emphasized the availability of reliable datasets (at least 50 years) in order to produce reliable results. Similar sentiment is expressed by Morid *et al*. (2006) who went further to stress the need for the index to reproduce spatial and temporal patterns of droughts.

2.2.3 Summary

In summary, this section has highlighted the advantages and disadvantages associated with using a particular index to characterize droughts. While various options are available, the ultimate decision to use an index rests primarily on the aims of the research, and the resources the researcher possesses (*e.g.*, data availability). Characterizing drought severity is far from straightforward because of the large temporal and spatial variability of droughts (Marsh, 2007). This can be resolved if the index is standardized hence removing the spatial bias, but it is still difficult to compare drought severities across indices owing to the different intensity scales used by the indices. In addition, although index intercomparison may show consistency in characterizing aspects of droughts, it is not known which index holds the "truth" if they have not been benchmarked against known hydrological features such as river flow or groundwater levels. This is important if the index is to be used as a proxy for assessment of water resources. Characterizing droughts over a given time scale (*e.g.*, 3-month drought) may be limited in that it may overestimate or underestimate drought frequency, severity and duration but this can be resolved by exploring droughts over multi-temporal scales.

2.3 Causes of droughts

It is difficult to attribute the causes of drought to one particular factor as a combination of factors is often involved in the occurrence of a drought. Droughts have been linked to various factors ranging from sunspot cycles to poor management strategies. Most of the causes have been well established judging from the body of literature available, whereas the influence of others is not strong. Drawing upon various studies, several of the commonly known factors, most having direct relationship with precipitation anomalies, are discussed below.

2.3.1 Prevalence of high pressure systems

The prevalence of high pressure systems (*i.e.*, anti-cyclonic conditions) over the study area has been strongly linked to drought occurrence, as have been shown by many (*e.g.*, Hastenrath *et al*., 1984; Hanson, 1991; Wilby, 1993; Mayes, 1996; Park and Schubert, 1997; Khandekar, 2004; Marsh, 2007). Hanson (1991) examined the nature of summer droughts in southeast of the United States and found frequent recurrence of high-pressure situations over the region. Fowler and Kilsby (2002a) showed that from 1881 to 1998, droughts in the Yorkshire region in the UK were associated with an increase in anti-cyclonic and a corresponding decrease in cyclonic weather-types. In their study in northeast Spain, Vicente-Serrano and López-Moreno (2006) observed that the increase in drought events from 1952 to 1999 was associated with anti-cyclonic weather patterns.

It is equally important to recognize the timing of the change in weather-type, not just the nature of change. In the context of water resource droughts, the timing of anti-cylonic conditions is vital as it affects the availability of precipitation for water resource systems (*e.g.*, groundwater, reservoirs and rivers) to recharge themselves (Parry *et al*., 2012). The prevalence of anti-cyclonic conditions during the recharge period, typically in winter, has severe impacts on summer droughts. In the UK, the incidence of summer hydrological droughts is often associated with anti-cyclonic conditions during the preceeding seasons. Such has been shown in the case of, for example, the 2004-2006 drought in southern Britain which originated from persistent anti-cyclonic weather patterns in late autumn of 2004 (Marsh, 2007).

Depending on their origin, winds can initiate, exacerbate or terminate a drought. Continental winds are more likely to initiate a drought as less moisture is transported along its route as opposed oceanic winds. Storm tracks have been noted to influence drought events. In 2001, northern Britain and Northern Ireland experienced drought when rain bearing frontal system followed a more southerly track than normal (Marsh *et al*., 2008). In the study of streamflow droughts in Europe from 1962 to 1990, Hisdal *et al*. (2001) attributed the regional differences in the trends in drought severity to the northward shift of the storm track and the stronger than average westerlies over the mid-latitudes.

2.3.2 Large ocean-atmosphere circulation modes

The behaviour of larger scale circulation patterns, such as the North Atlantic Oscillation (NAO) and the El Niño Southern Oscillation (ENSO), plays an important role in influencing not only the severity of drought (or precipitation anomaly) but also its spatial distribution. The influence of atmospheric circulation is however region specific *i.e.*, certain circulation types exert a stronger influence on the climate of certain regions more than others. For example, climate variability in Europe is strongly associated with the NAO, whereas climates of the Sahel and southern Africa are linked to the El Niño Southern Oscillation (ENSO).

There is spatial disparity in the relationship between the NAO index (NAOI) and winter rainfall in the UK. Wilby *et al*. (1997) showed significant positive correlations between winter NAO and rainfall amounts in northwest England, northern and southern Scotland but not in southern, central and northeast England which showed significant negative correlations. A similar north-south gradient was also reported by Murphy and Washington (2001) who showed increasing positive correlations from southeast England to northwest Scotland, and Fowler and Kilsby (2002b) who showed strong association between winter precipitation and the NAO based on their study in northern England. López-Moreno and Vicente-Serrano (2008) noted that the response of droughts to NAO varies in both time and space as has been shown in their study over Europe from 1901 to 2000 in which positive phases of the NAO are associated with droughts in southern, but not in northern Europe.

The influence of NAO and river flow in the UK has yet to be widely researched. Wedgebrow *et al*. (2002) highlighted the lagged influence of NAO on monthly river flow in which the authors reported weak negative relationship between winter NAO and summer flow but a positive relationship between winter NAO and autumn flow. Phillips *et al*. (2003) showed that during winter when the

NAO was more prominent, river flow variability demonstrates greater sensitivity to large-scale, than regional-scale, atmospheric processes. Nonetheless, the authors stressed that the sensitivity of river flow discharge may be related to catchment characteristics, rather than sensitivity of discharge to regional climate and atmospheric circulation variations.

In tropical regions, the influence of ENSO is more apparent. Studies have shown that droughts are strongly associated with the warm phase of ENSO *i.e.*, El Niño, whereas wetter-than-normal conditions are linked to its cold phase *i.e.*, La Niña (*e.g.*, Harger, 1995). The relationship between the extent of area under drought and ENSO was linear – strongly positive during El Niño and strongly negative during La Niña (Lyon, 2004; Lyon and Barnston, 2005). In addition, the response of precipitation/droughts to ENSO was seasonally and regionally dependent (Mo *et al*., 2009).

Although the occurrence and persistence of droughts may have been influenced by changes in atmospheric circulation, the relationship does not necessarily point to the fact that the impacts of such droughts are severe. This is because the predictability of atmospheric circulation changes, such as the see-saw effect of phases of ENSO, allows droughts to be predicted in years in advance (although operational forecasting is known to be skillful only a few months in advance), thus providing ample time for mitigation strategies (Goddard, 2001; Burt and Howden, 2013).

2.3.3 Temperature

In contrast with precipitation deficit which has a direct role in limiting the availability of water, the role of temperature on a region's vulnerability to drought is an indirect one. An increase in temperature will not only lead to increase demand for water. More importantly, the increase triggers an increase in evapotranspiration, hence lowering effective rainfall which in turn increases chances of hydrological droughts (Vidal and Wade, 2009).

The influence of temperature on droughts has been examined by Briffa *et al*. (2009) who observed that temperature is the major cause for the large spatial extent of summer drought in the last two decades in Europe. In southeastern Australia, rising temperatures since 1950 have shown to bear negative impacts on river flow amounts and soil moisture. Studies by Cai and Cowan (2008) and Cai *et al*. (2009) on the Murray Darling basin respectively showed that a 1 °C rise in temperature led to a 15 % decrease in annual inflow and a 9 % reduction in soil moisture.

2.3.4 Evaporation

Evaporation is a critical component in the water budget as it controls the availability of water of a region, hence its vulnerability to droughts. Rates of evaporation vary with season and across space, and are linked to the factors discussed above which may further speed up the rate and enhance drought conditions. The "pan evaporation paradox" which describes the discrepancy between decreasing trends of evaporation from pan measurements over the last

50 years despite increases in temperature only showed that evaporation is not influenced by temperature alone (Fu *et al*., 2009; Roderick *et al*., 2009; Sheffield *et al*., 2012). Other major factors contributing to the decrease in trends of pan evaporation include increases in solar radiation (Stanhill and Möller, 2008) and wind speed (Rayner, 2007).

2.3.5 Factors affecting droughts in the UK

Studies have shown that historical droughts in the UK are largely influenced by changes in atmospheric conditions, although the interplay between various factors such as soil moisture, evaporation and river flow and ground water levels was also evident (Marsh, 1996; Fowler and Kilsby, 2002a; Parry *et al.*, 2012). The 1995-1996 drought began with rainfall deficits, following the deflection of rain-bearing frontal systems and the import of subtropical air masses across Britain. The drought was further exacerbated with the high demand for water, primarily for gardening, which led to rapid depletion of reservoir and groundwater resources which had reached capacity-filled and seasonal maxima conditions, respectively, during the wet winter of 1994-1995.

The 2003 drought was preluded by the notably wet winter of 2002 when the Atlantic frontal systems followed a southerly track resulting in wet conditions over southern Britain and dry over the north (Marsh, 2004). The drought developed during late winter/early spring when rainfall was at its lowest since 1956 with less than 3 mm over 45 days during February-April 2003. The condition was moderated over late spring and early summer when rainfall was back to near average totals. However, high evaporation rates and the onset of record high temperatures (heat wave) in late July intensified drought conditions.

The 2004-2006 drought in southern Britain had its origin from the exceptionally dry and warm spring, summer and early autumn of 2003 (Marsh, 2007). Although the preceding winter was sufficiently wet, the very dry soil conditions during autumn of 2003 delayed the onset of seasonal recovery in runoff and groundwater recharge. Consequently, the spring of 2004 started with low groundwater levels. The lack of rainfall, as a result of persistent anti-cyclonic conditions over two successive winter/spring periods with maximum rainfall deficiencies exceeding 25 %, coupled with high evaporation demands resulted in large deficiencies in inflow from surface and groundwater.

Jones *et al*. (1997) noted that the spatial variability and severity of hydrological droughts in a given region were in part related to the type of its water resource system which has important influence in modulating droughts. Regions characterized by surface reservoirs (*e.g.*, northern and western upland regions) are associated with short duration droughts (up to 9 months), whereas those characterized by groundwater reserves (*e.g.*, central and eastern England) are associated with long duration droughts (15-18 months).

The spatial variability of droughts also reflects the nature of the prevailing meteorological conditions. The relationship between weather type and precipitation has been investigated in greater depth. Philips and McGregor (1998) argued that it is equally important to observe the positioning of the anti-cyclone, rather than the type of weather pattern per se, as it had a fundamental effect in determining the geographical distribution of droughts. They observed that droughts in the region were associated with either the northeast (*e.g.*, 1962-1963, 1964-1965 and 1995) or southwest (*e.g.*, 1975-1976, 1978 and 1992) positioning of the anti-cyclone. Fowler and Kilsby (2002a) classified droughts over the Yorkshire region as being "eastern" or "western" in which the former is characterized by the decrease in the occurrence of easterly and cyclonic easterly weather types, whereas the latter showed decrease in the occurrence of westerly weather types.

2.4 Historical droughts

2.4.1 Time series of global and regional droughts

Studies into the trends of droughts over the historical period have shown that droughts have generally become less severe, especially over the last 50 years. Sheffield *et al*. (2012) showed that global averaged time series of PDSI exhibited decreasing trends since 1970s. Their findings were consistent with results from earlier studies by Bordi *et al*. (2006) and Burke *et al*. (2006) who, respectively, reported decreasing global averaged SPI-24 and PDSI time series. To a large extent, the results also agree with the study by Tebaldi *et al*. (2006) who showed significant decreasing trend in observed dry days (although the authors' did not regard dry days as drought conditions). However, these studies contrasted with the work by Dai *et al*. (2004) and Dai (2011) who showed increases in global PDSI trend during the second half of the 20th century, especially since the 1980s.

Results from Sheffield *et al*. (and the like) are consistent with observations of decreasing pan evaporation trends as reported in many regions (Roderick *et al*., 2009), thus suggesting that the conclusions may well be representative of actual drought conditions which point to less severe droughts towards the end of the 20th century, contrary to the believe that droughts are expected to become more severe in light of a warming climate.

Focusing on regional domains, decreasing trends in the time series of drought indices have been reported by Idso and Balling Jr. (1992), Andreadis and Lettenmaier (2006), Bordi *et al*. (2006) for the US. Results for Europe were more variable. In the assessment of stream flow droughts, Hisdal *et al*. (2001) showed that it is not possible to conclude that drought conditions in general have become more severe as certain parts of Europe showed either increasing or decreasing drought deficit volumes. Briffa *et al*. (2009) on the other hand showed evidence of more occurring dryness based on summer PDSI values, whereas Bordi *et al*. (2006) showed decreasing trends in the time series of SPI-24 averaged over the Euro-Mediterranean region.

2.4.2 Area under drought

In terms of area, increases in the trends of drought area have been reported in some studies, whereas decreases (or no change) have been documented in others. Sheffield *et al*. (2009), for example, showed increase in trends in the area under droughts, more prominently over Africa and East Asia, from 1980 to 2008 as simulated by the PDSI. In Europe, Bordi *et al*. (2009) reported increasing trend in the percentage of grid points under drought based on SPI-3 for the period 1950-2010. Lloyd-Hughes and Saunders (2002) showed increasing trends in the proportion of Europe under extreme and/or moderate droughts. However the rate of increase was reported to be insignificant. On the other hand, downward trends in drought areas based on moisture and runoff data were reported by Andreadis and Lettenmaier (2006) for the US.

2.4.3 Duration and/or frequency

Drought duration largely showed decreasing trends as has been shown by Andreadis and Lettenmaier (2006) in the case of the agricultural and hydrological droughts in the US. This contrasted with results of European study by Lloyd-Hughes and Saunders (2002) who showed increase in mean duration of extreme and moderate droughts at various time scales. However the authors noted that longer droughts were rare, although the decreases in the frequency of extreme and moderate droughts were generally shown.

2.4.4 Historical droughts in the UK

There have been numerous studies reporting on historical droughts in the UK in which a large proportion addressed hydrological droughts, had strong regional focus and highlighted their spatial variability. In these cases, the severity of drought was primarily expressed in terms of rainfall deficiency, although other indices have also been used (Phillips and McGregor, 1998; Marsh, 2004). To an extent, it forms a challenge to try to put historical droughts in the UK within the context of global and regional droughts in terms of changes in severity, area, duration and/or frequency over the course of the 20th century as discussed in earlier sections. This is because the scope of most drought studies in the UK sought to understand the development of droughts, and by doing so, adopted an event-based approach (*e.g.*, Parry *et al*., 2012).

Marsh *et al*. (1994) presented work on the 1988-1992 drought which affected the entire UK. The event saw a strong north-south division of drought impacts with precipitation excess over most of Scotland but severe deficit (averaging 70-75 % below the long term mean of 1941-1970) over England and Wales, greatest over Northumbria/Yorkshire and, to an extent, the Thames region. Spatial disparities in rainfall deficit were also observed in several other drought events. The 2004-2006 event showed severe deficiencies over southwest (Cornwall) and southeast England, but excess over the Scottish Highlands (Marsh *et al*., 2008). The 1995-1996 drought focused on northern England which experienced rainfall return period estimates of 50-70 % of the 1961-1990 mean (Marsh, 1996). As with the droughts of 1988-1992 and 2004-2006, much of Scotland experiences higher return period estimates (about 80-120 %).

Even within the regional context, there exists appreciable local variation. This has been confirmed by Marsh (2007) in the study of the 2004-2006 drought which showed notable difference over southern Britain, especially the southwest (Cornwall) and southeast England, with maximum rainfall deficiencies exceeding 25 %. Philips and McGregor (1998) examined drought situations from 1962-1995 over southwest Britain in greater detail using four locations at Devon and Cornwall and observed mixed results. They detected more severe droughts at the northern coastal site during the 1962-1963 and 1964-1965 events. During the 1983-1984 drought, there was high degree of variability across the four locations but for the 1992 drought, there was high degree of spatial coherence (in terms of duration). Fowler and Kilsby (2002a) also noted high spatial variability in the Yorkshire region which they attribute the reason to weather-types.

2.5 Future droughts

2.5.1 Time series of global and regional droughts

There is consensus amongst global and regional studies that droughts are projected to increase in severity in the future. Sheffield and Wood (2008) showed increasing trends of global averaged time series of mean drought severity for SRESA2, A1B and B1 emissions scenarios for the period 1900-2100 using eight GCMs participating in the IPCC's Fourth Assessment Report (AR4). They showed that the increase in the trends of drought severity was matched with corresponding decrease in trends of soil moisture. In the study by Tebaldi *et al*. (2006), there was good agreement across nine AR4's GCMs which showed statistically significant increases in the global averaged trends of dry days and heat waves under the SRESA2, A1B and B1 scenarios. Similar conclusions were reported by Burke *et al*. (2006) who, using the HadCM3, showed decreasing trends in global average PDSI (indicating drying trend), with a greater rate of decrease projected for the second half of the 21st century.

Results of regional projections of drought severity are largely consistent with global analysis. This was shown, for example, in the case of the US with sharp increases projected in the severity of 21st century droughts based on the simulation from 18 AR4's GCMs under the SRESA1B emissions scenario (Gutzler and Robbins, 2011). Using HadCM3, Warren *et al*. (2012) showed the intensification of drought conditions in Europe during the second half of the 21st century under five SRES emissions scenarios, with Mediterranean regions and southern Europe showing prominent increases in severity and with less prominent drying shown over southern England. Intensification of drought conditions during the second half of the 21st century was also shown in the Thessaly region in Greece (Loukas *et al.*, 2008).

2.5.2 Area under drought

There is agreement across studies that more areas are expected to be under droughts in the future. Sheffield and Wood (2008) showed that globally, trends of drought area for the period 2000-2100 are projected to increase by 20 %, with prominent increases shown over Mediterranean, west and southern Africa, central Asia, central North America and Central America. The authors' findings are consistent with results from Burke *et al*. (2006) who reported increases in the percentage of area under drought under extreme, severe and moderate droughts to 30%, 40% and 50%, respectively by 2100. Similarly, Kirono *et al*. (2011) showed that drought extent in most regions in Australia would have doubled by 2100.

2.5.3 Duration and/or frequency

In addition to the projected increases in the extent and severity of droughts, studies point to the increase in drought duration and/or frequency in the future. Sheffield and Wood (2008) showed that there was an increase in global and regional trends in the frequency of short- (4-6 months) and long-term (>12 months) droughts towards the end of the 21st century. The conclusion was also supported by several other studies (Burke *et al*., 2006; Taylor *et al*., 2013). Burke *et al*. (2006) showed that globally, future droughts are getting more frequent and longer in duration. Similarly, in the study by Taylor *et al*. (2013), there was agreement across the four drought indices showing significant increases in time spent in drought for the 2080s for several regions: Central America, Amazon, southern Chile, Mediterranean, northwest and southern Africa. For other regions, the authors noted that contrasting signals between indices were apparent.

Regional studies are in general agreement with global projections. In the US, Gutzler and Robbins (2011) found sharp increases in the duration of 21st century droughts. In Australia, Kirono *et al*. (2011) showed increases in frequency of droughts in all regions except north and central Queensland. In Europe, Blenkinsop and Fowler (2007a) concluded that there is higher frequency of longer duration (6 months) droughts over southern, western and central Europe. On the contrary, the ensemble of RCMs projected a decrease in short duration (3 months) droughts across Europe. Nonetheless, the authors reasoned that the projected decrease was associated with a lower degree of inter-model consistency. Results from the study by Warren *et al*. (2012) concluded that both the frequency of 5- and 12-month droughts showed increases, with the former showing higher frequency. The authors suggested that climate change tends to increase drought frequency rather than drought length.

2.5.4 Future droughts in the UK

Existing studies have shown that in the 21st century, droughts in the UK have been projected to increase in frequency, duration and/or severity (*e.g.*, Fowler and Kilsby, 2004; Vidal and Wade, 2009). The findings agree with the UKCP09's projection of drier summers for the UK resulting from decrease in precipitation and increase in mean temperature for the 2050s (Murphy *et al*., 2009), suggesting the strong relationship between droughts and warmer climates for the UK. The projected intensification of drought characteristics is consistent with global and regional droughts projected for the future.

The study by Fowler *et al*. (2003) showed 18 % and 34 % increases (relative to the period 1961-1990) in the duration of droughts in the Yorkshire region for the period 2021-2050 and 2051-2080, respectively using data from HadCM2 GCM. Increases in drought severity and frequency have been reported by Fowler and Kilsby (2004) in most regions in the UK for the period 2070-2100 although the authors acknowledged the overestimation and underestimation of drought characteristics in different parts of the UK by the RCM when evaluated against the observed dataset.

Using an ensemble of RCMs as part of the European PRUDENCE project, Blenkinsop and Fowler (2007b) reported an increase in short-term summer droughts for the period 2071-2100, whereas long-term droughts were projected to become shorter and less severe. The results were however inconclusive as the authors noted large variability in projections by the RCMs. Using a multi-model GCM experiment, Vidal and Wade (2009) observed spatial variability in the results. Results for the 2020s, relative to the 1970s, showed slight increase in the frequency of extreme droughts for south of England. The 2050s showed large decrease in drought frequency for most of England except for the southeast, whereas the 2080s exhibited a north-south contrast with higher increase in the frequency of drought in England, in particular the southeast.

In a perturbed-physics ensemble (PPE) experiment using 11 variants of the HadRM3 (HadRM3-PPE-UK), Burke *et al*. 2010 showed overall increases in future droughts for the period 2000-2098 (relative to the mean of 1961-1990) of up to 20 % for area-averaged droughts. Their results, however, were associated with considerable spread of values showing little change to significant increase depending on the ensemble member. In another study using the same HadRM3-PPE-UK dataset, Burke and Brown (2010) showed no distinct signal in the projected changes in drought severity, frequency and area with the ensemble member showing ±20 % change for the period 2049-2099, relative to the period 1951-2001 for England and Wales. There was better consensus across models for Scotland and Northern Ireland which showed a decrease in drought frequency.

Changes in river flow are also consistent with projections of 21st century meteorological droughts. This has been shown in the study by Prudhomme *et al*. (2012) who showed decreases in summer flow for the 2050s, with large decreases in the north and west of the UK.

2.6 Summary of review

This chapter has highlighted some of the common factors that influence droughts. The vulnerability of a region to droughts is primarily determined by changes in these factors which, to a large extent, are mutually-reinforcing. In the UK, in addition to these factors, the type of water resource systems (*e.g.*, groundwater or reservoirs) plays an equally important role in defining not only the nature of droughts (*e.g.*, frequency and duration) that a region experiences but also its vulnerability which can be exacerbated by anthropogenic activities, such as over-abstraction of water resources and modifications to the catchment's characteristics (*e.g.*, changes in land use and land cover). A region's eventual exposure to droughts rests on the ability of authorities to manage water resources which will then determine speed at which it recovers from droughts or the duration it stays in one. In this context, an example can be drawn from UK's contrasting experience with the 1995 and 2005 droughts. The 2003 drought illustrated how integrated management of water resources resulted in a modest impact of drought in the country as a whole (Marsh, 2004). This contrasted with the 1995 drought which had stress because of poor management of water resources (Marsh, 1996; Walker and Smithers, 1998).

There is evidence to show that droughts at the end of the 20th century were generally more frequent, shorter in duration and less severe. Although the finding is in agreement across global and regional studies, there is also a degree of inconsistency across studies. This can potentially be attributed to the different methods of analysis in the form of drought indices, datasets, types of droughts (*e.g.*, meteorological and hydrological) and time frame. In the context of the UK, analysis on historical droughts has largely focused on understanding the development of event-based droughts, in contrast with the trends of drought characteristics (*e.g.*, severity, frequency and/or duration) over the historical period. Trends in seasonal rainfall and river flow, showing increases during winter and decreases during summer since 1970s (Marsh *et al*., 2007; Hannaford and Harvey, 2010), could at best suggest the likelihood of drought intensification towards the end of the century. Major hydrological droughts in England and Wales (1921, 1933, 1947, 1959, 1976, 1995, 2003 and 2004-2006) only show that drought is a recurring feature of the UK's climate with severe event occurring every 10 years (Marsh, 2004; Marsh *et al*., 2007). They do not point to any trend in drought characteristics. Neither do the trends in the aridity index for England and Wales which showed only modest increase over the last 100 years (Marsh, 2004). The lack of studies on the trends of 20th century drought characteristics in the UK therefore means that it is difficult to put UK's experience within the context of wider regional and global drought trends.

In the context of future droughts, there is strong consensus across studies that droughts are projected to intensify towards the end of the 21st century. The likelihood of increased drought occurrence and/or severity in the 21st century largely reflects the future changes in precipitation, runoff, soil moisture and evaporation (Wetherald and Manabe, 2002; IPCC, 2007). Despite the agreement, uncertainties in global and regional projections of droughts remain, some of which are related to the unavailability of data for a given region or variable (*e.g.*, soil moisture) for model evaluation and the choice of drought index (Burke and Brown, 2008).

Projections of future droughts in the UK are generally consistent with that of global and regional analyses, although the uncertainties, especially in the magnitude of change, associated with these studies can be large (*e.g.*, Burke and Brown, 2010; Burke *et al*., 2010). Recent studies have seen the utility of UKCP09 climate scenarios which represent a fundamentally different methodological and analytical approach to climate projections compared with previous UKCIP02 scenarios (Burke *et al*., 2010; Burke and Brown, 2010; Prudhomme *et al*., 2012). While these studies have shown the usefulness in the perturbed physics ensemble approach in the understanding of uncertainties and presented information on drought behavior given a new scenario (*i.e.*, UKCP09), more work – in addition to those in Table 2.2 – such as presenting alternative analysis, investigating new or revisiting existing drought characteristics is needed to robustly enhance our understanding of drought behavior and their uncertainties in the future.

Table 2.1: Description, advantages and disadvantages of some of the commonly used indices in drought literature.

Index (Reference)	Description	Advantages	Disadvantages
z-score	Calculation is based on the number of standard deviations below or above the mean	Simple to compute; standardization allows spatial comparison of droughts	Negative z-scores have negative connotations; Not easily interpreted.
Bhalme-Mooley Drought Index (BMDI) (Bhalme and Mooley, 1980)	Recursive index in which successive calculations of the index depended on the prior month's value.	Index has been developed specifically for India but can be adapted to different regions.	Relatively complex calculation; development of the index is based on the assumption that plants and human activities in a region are adjusted to average rainfall conditions – therefore not suitable for regions with extremes.
Theory of runs	Based on the succession of a variable's quantity (*e.g.*, duration of rainfall deficit) that falls below (or exceeds) the chosen critical threshold.	Computationally simple.	Data changes according to threshold changes; Time series are not normalized, hence making it difficult for spatial comparison.
Palmer Drought Severity Index (PDSI) (Palmer, 1965)	Index is based on the moisture supply anomaly. It draws on the water balance concept, taking into account supply and demand changes in soil moisture, precipitation, and temperature.	Widely tested and used index to detect agricultural droughts.	Lagged detection of drought; Less suited non-homogeneous regions; Computationally complex
Soil Moisture Anomaly Index (Burke and Brown, 2008)	Based on the departure of soil moisture from the normal climate.	Index has been developed to characterize agricultural drought.	Not a practical drought index because of limited observations of soil moisture
Drought Severity Index (DSI) (Phillips and McGregor, 1998)	Method based on standardized cumulative precipitation anomaly.	Flexibility of time scale allows both meteorological and hydrological droughts to be detected.	Choice of time scale affects the frequency and duration of droughts.

Standardized Precipitation Index (SPI) (McKee *et al*., 1993)	Index based on the probability of precipitation for any time scale.	Computationally simple; requires only precipitation data. Flexibility in time scale allows detection of drought at any duration.	SPI values are determined by a probability density function that best describes the long term precipitation data. The use of different probability distribution function results in different SPI values.
Standardized Runoff Index (SRI) (Shukla and Wood, 2008)	An extension of the SPI but incorporating hydrological and meteorological processes that influence the volume and timing of streamflow.	Identifies potential hydrological droughts. Advantages are similar to that of SPI.	As SPI.

Table 2.2: Summary of 21st century drought studies in the UK

Author (Year)	Model	Scenario	Index	Characteristic	Main findings
Fowler *et al.* (2003)	HadCM2 (GCM)	Medium-high climate change scenario from UKCIP98 for 2021-2050 and 2051-2080.	RRV* indices	Droughts are expressed as percentage change in rainfall amount and average water supply.	Slight increase in frequency of severe droughts by 2080s. Significant increases in magnitude and duration of droughts due decreased summer rainfall and increased climatic variability.
Fowler and Kilsby (2004)	HadRM3H (RCM)	IPCC SRES A2 and B2 (UKCIP02 medium-low) emissions scenarios for 2070-2100.	Short and long droughts (3-6 and >6 months) based on the DSI.	Maximum duration, maximum severity and frequency of drought events.	Increase in drought frequency and severity in most regions, particularly south and east of UK, by the end of 21st century.
Blenkinsop and Fowler (2007b)	Six PRUDENCE RCMs	IPCC SRES A2 emissions scenario for 2071-2100	3- and 6-month DSI	Frequency, maximum severity and maximum duration.	Projected increase in short term summer drought in most water resource regions. Longer duration droughts are projected to become shorter and less severe.
Vidal and Wade (2009)	Six GCMs	IPCC SRES A2 and B2 emissions scenarios for 2020s, 2050s and 2080s.	3-, 6-, 12- and 24-month SPI	Frequency and mean magnitude of extreme droughts.	Increase in frequency of short-term extreme drought for A2 scenario across the UK, with large increases in the southeast. Long-term droughts showed mixed results: little change (southern to midland), significant decrease (northern) depending on the future period.
Burke and Brown (2010)	11-member HadRM3 (RCM)	IPCC SRES A1B for the period 2049-2099	12-month accumulated precipitation anomaly	Area-Probability (Area-P) and Severity-area-frequency (SAF).	Indistinct signal. Ensemble members either show increase or decrease in frequency of drought, Area-P and SAF.

Burke *et al.* (2010)	11-member HadRM3 (RCM)	IPCC SRES A1B for the period 2000-2098	3-, 6-, 12- and 18-month precipitation anomalies	Return level	Drought indices show overall increase in future drought, but the spread of results across ensemble members is considerable.
Prudhomme *et al.* (2012)	11-member HadRM3 (RCM)	IPCC SRES A1B for the 2050s.	Not applicable	Droughts expressed as changes mean seasonal flow	Decrease in summer flow predominantly showed across ensemble members, whereas mixed pattern with drier, similar, or wetter signals shown in winter. Marked variations between RCM scenarios.

* RRV: Reliability, resilience and vulnerability

Chapter 3

Research Questions

Following the review of literature in Chapter 2, this chapter identifies caveats in existing research as well as new aspects which could propel drought research forward. Although there are potentially many, only four research gaps will be identified. These gaps will form the core research of this thesis.

3.1 Credibility of rainfall-based indices to represent hydrological droughts

Drought indices have been evaluated against one another to determine which is more reliable or suitable in characterizing droughts. Often the results show limited consistency across indices as some indices are better in detecting certain characteristics but poor in others. A major shortfall is that both rainfall-based and water-balance indices have not been evaluated against hydrological features such as river flow. This is an important gap especially for rainfall-based indices which, because of their unidata requirement, are often conveniently used as a tool to study the impacts of droughts on water resources. The apparent lag between meteorological droughts (as simulated by a rainfall-based index) and hydrological droughts (as represented by river flow), owing to modulating factors that include geology, soil types and catchment geometry, suggests that there are differences in timing, duration and intensity between the two drought types. The ability of rainfall-based drought indices to reproduce temporal variability of river flow therefore presents a major gap in our understanding of utility of such index for water resource planning and management.

In Chapter 4, the thesis investigates the ability of a rainfall-based drought index, the drought severity index (DSI), to simulate hydrological droughts. In this chapter, the DSI is applied to both rainfall and river flow data to assess whether the characteristics of droughts generated by the rainfall-based index are consistent with that of the flow-based index. Examples from seven benchmark catchments in England are used to illustrate the study.

3.2 How coherent are droughts?

Although there have been numerous drought studies, each addressing specific aspect of a drought characteristic such as its intensity, duration and frequency, spatial coherence is one characteristic which has appeared only occasionally in the literature (*e.g.*, Phillips and McGregor, 1998; Burke *et al*., 2010; Hannaford *et al*., 2011) and hence is not well understood. This is important because from a water resources perspective, spatially extensive droughts can be particularly damaging because water deficits in one part of a catchment or operating region cannot be compensated in other parts. Analysis of the spatial coherence of droughts therefore provides an understanding of regional drought-risk so that better drought management strategies can be implemented.

In Chapter 5, a new methodology is introduced to quantify the spatial coherence of droughts for the UK for the historical period from 1914 to 2006. The technique, based on the concept of common drought months between any two grid points, is computed at each grid point in the observed rainfall dataset to characterize the coherence of droughts under different drought duration and severity conditions.

3.3 Methods of evaluating climate models

A common gauge of confidence in the ability of climate models to project future climates is the ability of the models to represent the spatio-temporal characteristics of climate of the recent past (Randall *et al.*, 2007). There is no universally agreed method in which a climate model can be evaluated (Räisänen, 2006; Dessai and Hulme, 2008; Schaller *et al.*, 2011) – this presents both a limitation and an opportunity for researchers. Climate models are commonly evaluated in terms of their ability to reproduce the observed rainfall (or temperature). The use of such an evaluation approach in drought studies may produce misleading results because the application of a drought index as frequently used in drought studies may involve some form of data transformation resulting in an index time series which may have a new probability distribution compared with the original data to which the drought index has been applied. The new index time series, therefore, may have different statistical characteristics than the original rainfall (or temperature) data. In drought studies, work to evaluate climate models in terms of their ability to reproduce present-day drought characteristics is rare. This presents a new opportunity to assess the consistency of techniques arising from the evaluation of statistical characteristics of a given climate variable (*e.g.*, temperature and rainfall) and statistical characteristics of droughts.

In Chapter 6, an evaluation of 11-member HadRM3 RCM from the PPE experiment (HadRM3-PPE-UK) is presented. In this chapter, the RCMs are assessed in terms of their ability to simulate four drought characteristics, namely drought intensity, spatial coherence, frequency of drought months and frequency of drought events at a given duration. In addition, this chapter seeks to investigate some of the factors which account for the biases in drought characteristics found in the RCMs.

3.4 Will future drought characteristics change?

Progress in climate modeling has resulted in more sophisticated and improved versions of climate models in terms of, for example, higher spatial and temporal resolutions, and better representation of sub-grid scale processes. The new generation of climate models, which is arguably more realistic given that our understanding of the climate system has progressed as well, calls for a revisit of climate projections and impacts assessment. The perturbed-physics ensemble (PPE) experiment presents a state-of-the-art technique to explore uncertainties in climate projections (Bellprat *et al*., 2012). It gives a picture of the evolution of climate for the past and future periods and, in its application to drought studies, provides users with the range of possible scenarios from which future drought risk can be better understood. This in turn could provide valuable information for water resources planning and management.

In Chapter 7, analysis of changes in drought characteristics for the UK for the 2020s, 2050s and 2080s, relative to the 1980s, using the same data from the HadRM3-PPE-UK (as in Chapter 6) is presented. Consistent with the preceding chapters, four drought characteristics, namely drought intensity, spatial coherence, frequency of drought months and frequency of drought events at a given duration, are examined. Two of the characteristics, spatial coherence and frequency of drought events at a given duration, have not been researched and hence future changes in these characteristics shed new information on drought behaviour.

Chapter 4

Does a Rainfall-based Drought Index Simulate Hydrological Droughts?

Abstract

This chapter is based on the following paper which has been submitted to *International Journal of Climatology* and is currently under revision for minor changes:

Rahiz M and New M (2013; *In revision*) Does a rainfall-based drought index simulate hydrological droughts? *International Journal of Climatology*.

This chapter addresses the first objective of the thesis: "*To assess the suitability of a rainfall-based drought index in representing hydrological droughts*". The rationale of this paper stems from the need to gauge the credibility of using such an index with gridded observed and RCM rainfall data in the assessment of droughts from a water resource perspective, which would, in turn, inform management and planning decisions.

The drought severity index (DSI) is applied at *n* month time scales (where *n* = 3, 6, 12 and 24) to both monthly gridded rainfall (MGR) and monthly river flow (MRF) datasets to evaluate if this particular rainfall-based drought index is able to represent hydrological droughts. Time series of the flow-based and rainfall-based DSIs ($MRF_{DSI\text{-}n}$ and $MGR_{DSI\text{-}n}$, respectively) are analyzed under extreme and moderate drought severities, and for the dry and wet seasons at seven benchmark

catchments in England. The analysis also assesses the ability of the indices to reproduce the statistics of three drought characteristics: drought intensity (*DI*), frequency of drought months (*FDM*) and frequency of drought events at a given duration (*FDD*).

Results of this study show the following: 1) the DSI is able to capture periods of low flows as can be seen in the ability of the $MGR_{DSI\text{-}n}$ in capturing major drought events as simulated by the $MRF_{DSI\text{-}n}$; 2) the $MGR_{DSI\text{-}n}$ generally represents moderate hydrological droughts better than extremes as shown by the smaller difference between $MGR_{DSI\text{-}n}$ and $MRF_{DSI\text{-}n}$ based on the statistics from the three drought characteristics; and 3) there is a positive relationship between the time scale of DSI and the intensity (and duration) of the drought event it produces *i.e.*, a longer time scale DSI (*e.g.*, 12-month DSI) produces droughts which are more intense and longer in duration compared with DSI with a shorter time scale (*e.g.*, 3-month DSI). As a secondary objective, the study has shown that the MGR is a good proxy for catchment rainfall and can therefore be considered a reliable dataset for representing catchment scale rainfall in historic and climate change analyses.

The significance of the study is that the results identify the DSI as a credible index in estimating hydrological droughts. The close correlation between rainfall and hydrological DSI time series suggests that changes and trends in rainfall-based DSI can provide useful inferences for understanding changes in future hydrological droughts, as well as meteorological droughts. Therefore, analyses using a rainfall-based DSI can provide useful information in the assessment of drought impacts and future planning and management of water resources.

4.1 Introduction

The measure of a drought event is often expressed by an index which gives its intensity and duration. Numerous indices, ranging from the simplest to more complex in terms of their formulation and data requirements, have been introduced to achieve this characterization. Nonetheless, these indices merely provide a standardized measure of some aspect of water deficit; they still require interpretation to relate the index to drought impacts in any particular sector (Phillips and McGregor, 1998).

Drought indices can be categorized into two types: those which are solely based on rainfall *e.g.,* the standardized precipitation index (SPI - McKee *et al.*, 1993) and those which additionally factor in the terrestrial water budget *e.g.,* the Palmer drought severity index (PDSI - Palmer, 1965). To date, studies have compared either categories of indices (*e.g.*, Oladipo, 1985; Morid *et al.*, 2006) or a combination of both water balance indices and those which are rainfall-based (*e.g.*, Ntale and Gan, 2003).

In theory, indices, via their standardized approach, allow for the comparison of droughts from one region with another, as well as for comparing events at different temporal scales (Marsh *et al.*, 1994). However, the truth is far from straightforward as studies have shown that while the performance of the indices is comparable with one another, there remain several aspects in which they disagree. For example, Morid *et al.* (2006) found inconsistencies in terms of the responsiveness to rainfall events and the spatio-temporal behaviour values of seven drought indices. Ntale and Gan (2003) concluded that the SPI is more appropriate in characterizing East African droughts than the PDSI which is designed for the United States. This conclusion, and those from other studies, led to the claim that the performance of drought indices is region specific (Mishra and Singh, 2010).

4.2 Research aim

Comparison of rainfall-based drought indices lends a useful insight on how they perform but they are often not evaluated against their relevance for drought sensitive systems, such as rivers and groundwater aquifers. Owing to modulating factors that include geology, soil types and catchment geometry, hydrological drought can have different characteristics than meteorological drought, in terms of timing, duration and intensity. For example, a lag between the occurrence of rainfall deficit and hydrological drought was shown in the case of the UK where hydrological droughts during the summer months are often associated with dry conditions of the preceding winter (Marsh *et al.*, 2007).

The primary aim of this study is to assess the performance of a rainfall-based drought index in reproducing the temporal patterns of river hydrological droughts and other statistical characteristics of drought. The study investigates issues such as: (a) is the rainfall-based drought index able to capture periods of low flows?, (b) can extreme (or moderate) droughts simulated by the rainfall-based index represent correspondingly extreme (or moderate) drought conditions in river flow?, and (c) what are the implications of varying the time scale of a drought index?. A secondary aim is to assess if gridded observed rainfall data are representative of rainfall conditions at the catchment scale as gridded data are often used as the main dataset for regional/country-wide climate impacts assessment. The outcome of this study provides a gauge of the usefulness of using such a rainfall-based drought index for future planning and management of water resources.

4.3 Methodology

4.3.1 Data

The 5 x 5 km monthly gridded rainfall (henceforth MGR) (Perry and Hollis, 2005) spanning 1914-2006 for the entire UK is used. In this study, the dataset has been re-gridded to a regular longitudinal-latitudinal grid of 0.225° to retain consistency with the authors' related work on droughts in the UK (*e.g.*, Rahiz and New, 2012; 2013). Two additional datasets, monthly river flow (MRF) and catchment monthly rainfall (CMR), obtained from the National River Flow Archive (NRFA) (http://www.ceh.ac.uk/data/nrfa) serve as reference datasets against which the MGR is evaluated. The use of CMR is to assess the consistency of the MGR in terms of its spatial and temporal patterns of rainfall. The MRF, on the other hand, allows the relationships between meteorological and hydrological droughts to be assessed.

For all datasets, data from seven benchmark catchments in England are extracted as examples to illustrate the study. Benchmark catchments provide a useful resource for assessment of climate-hydrology associations (Laizé and Hannah, 2008). Although not absolutely natural, they minimize anthropogenic influences (*e.g.,* abstraction, and storage) on river flow, thus provide a better and accurate signal in terms of natural variability in the river flow (Bradford and Marsh, 2003; Hannaford and Harvey, 2010). Data for the benchmark catchments undergo annual quality control in the form of validation and resolution of the river flow time series, and with additional datasets, such as monthly catchment-averaged rainfall, provide tools for further validation and quality control (Fry and Swain, 2010)

The locations of the benchmark catchments, with physical characteristics detailed in Table 4.1, cover the seven main regions in England *i.e.*, northwest, northeast, Thames, Anglian, Midlands, southwest and southeast (Figure 4.1). The data are site-specific and are no means representative of conditions in other locations. Datasets for each catchment have varying start and end dates; only the common start date across datasets is used.

4.3.2 Drought severity index

A rainfall-based index, the drought severity index (DSI - Phillips and McGregor, 1998), is applied at 3-, 6-, 12-, and 24-month time scales to monthly gridded rainfall (MGR) and monthly river flow (MRF) (henceforth $MGR_{DSI\text{-}n}$ and $MRF_{DSI\text{-}n}$, respectively) data to characterize intra- and inter-annual droughts. The DSI refers to the cumulative anomalies of precipitation at an *n* month time scale, with the anomaly defined as the departure from the mean of a reference period (the monthly mean of 1961-1990 is used in this study).

The DSI has been utilized in a several UK studies for the assessment of regional drought risk (*e.g.*, Phillips and McGregor, 1998; Fowler and Kilsby, 2002a). In these studies, the choice of using the DSI is primarily based on the simplicity of its calculation and requiring only rainfall data, unlike other indices which are algorithmically more complex, data intensive and/or require some form of data transformation (*e.g.*, fitting a distribution curve to the dataset).

DSI values are positive, denoting drought conditions; a zero or negative value signals the termination of drought sequence following the set of rules defined in the algorithm, described below using the example of a 3-month DSI (DSI3) (after Phillips and McGregor, 1998);

Consider the rainfall anomaly in month t, denoted X_t. If X_t is negative (*i.e.*, below its mean level) and rainfall in the 3-month period, X_t, X_{t-1}, X_{t-2}, is lower than its 3-monthly mean, then initiate a drought sequence in month t, assigning the DSI a positive value that is equal to the precipitation deficit in month t.

Now consider the month $t + 1$. Suppose the rainfall anomalies in months t and $t + 1$ were $-X$ mm and $-Y$ mm, respectively, then the DSI3 for month $t + 1$ equals $X + Y$, if and only if the 3-monthly mean total for the months $t - 1$, t and $t + 1$ has not been exceeded. If the rainfall anomaly is positive in month $t + 1$, then a drought can continue, with DSI3 = $X - Y$, provided that the 3-monthly mean total has not been exceeded. All drought sequences are terminated immediately when this 3-monthly mean total has been exceeded and DSI3 is assigned a value of zero.

The index is then standardized by dividing the DSI3 values by the location's mean annual rainfall and then multiplying by 100. This standardization allows for inter-station comparison of drought severity (Phillips and McGregor, 1998). The final index value will thus express the accumulated precipitation deficit as percentage of the mean annual rainfall of the location. The calculation of DSI at other time scales follows the same principle as shown for DSI3, but using an *n* month accumulation and mean.

4.3.3 Seasonal disaggregation

The time series of all datasets are separated into the dry (summer) and wet (winter) seasons, covering the months of April-September and October-March, respectively following the procedure by Rahiz and New (2012). The half-year classification reflects the general hydrological calendar for the UK and describes hydrological cycle of storage (*e.g.*, groundwater recharge) and loss (*e.g.*, evaporation). The seasonally disaggregated datasets would therefore comprise the DSI-*n* values for the months of April-September (for the dry season) and October-March (for the wet season) of each year for the entire period.

4.3.4 Drought characteristics

The statistics of three drought characteristics, derived from $MRF_{DSI\text{-}n}$ and $MGR_{DSI\text{-}n}$ at each catchment, are used (after Rahiz and New, 2013):

- Drought intensity (*DI*), defined as the *k* percentile exceedance of DSI-*n* for a given season, where *k* = 95th, 90th, 70th, and 55th percentiles;

- Frequency of drought months (*FDM*), defined as the number of drought months within a given season that exceeds the *k* percentile of the entire DSI-*n* time series; and

- Frequency of droughts at a given duration (*FDD*), defined as the number of drought events with persistence of at least 3, 6, 10 and 12 months that exceeds the *k* percentile of the entire DSI-*n* time series. [Note: No seasonal subsetting is performed on *FDD*].

4.4 Results

4.4.1 Comparison between MGR and CMR

Comparison of the entire time series between MGR and CMR shows very good agreement between the datasets (Table 4.2): very high Spearman's correlation (*rho* ≥0.96) at the 90 % confidence level and small standard deviation (highest for East Dart). Values of mean absolute error (MAE) are small for Bedburn Beck, Beult, Lambourn and Lud, and largest for the remaining catchments. Large MAE are associated with a larger mean, thus when the mean absolute percentage error (MAE_p) is considered, the values are comparable across all catchments.

4.4.2 Comparison between $MGR_{DSI\text{-}n}$ and $MRF_{DSI\text{-}n}$

4.4.2.1 DSI3

In general, MGR_{DSI3} is well correlated with MRF_{DSI3} (Figure 4.2). However, the river flow index shows higher intensity and longer duration especially for extreme droughts. In some of the longer duration flow-based drought events, the rainfall DSI is also not as consistently positive, showing occasional breaks before becoming positive again. All catchments show reasonably good correlation (*rho1*) significant at the 90 % confidence level, which could be the product of the highly autocorrelated time series in both the MGR_{DSI3} and MRF_{DSI3} (Table 4.3). However, there is no difference in the new correlation values (*rho2*) after correcting the autocorrelated time series using the Cochrane-Orcutt transformation (Cochrane and Orcutt, 1949).

The high correlation magnitude at East Dart is because of several factors which contribute to the flashiness of the river (and hence MRF_{DSI3}): small catchment size, steep topography and high proportion of low permeability bedrock. The combination of larger size, gentler topography and more permeable geology at other catchments explains the lower correlation, resulting in the later occurrence (and termination) of the flow-based droughts due to the contribution of rainwater to groundwater recharge, in contrast with the easier termination of the rainfall-based drought following short but intense rain events.

4.4.2.2 DSI6

The temporal variability of droughts simulated by MRF_{DSI6} and MGR_{DSI6} is consistent with each other, with both indices able to replicate the major droughts well (Figure 4.3). MRF_{DSI6} droughts have larger magnitudes, longer duration of persistence and terminate 1-3 months later than those simulated by MGR_{DSI6}.

There is better correlation between the two datasets due to the effect of smoothening out shorter duration droughts.

4.4.2.3 DSI12

The DSI12 is less sensitive towards short but intense rainfall events and smooths out more short duration droughts (Figure 4.4). In most cases, DSI12 droughts are a combination of multiple short duration droughts, hence giving the droughts comparatively greater intensity, longer duration of persistence, and a later termination period. Resultantly, there is higher correlation value, with an average of 0.67, between MRF_{DSI12} and MGR_{DSI12} compared with DSI3 and DSI6 (average of 0.45 and 0.56, respectively) (Table 4.3).

4.4.2.4 DSI24

Time series of DSI24 are characterized by low frequency but long duration droughts spanning at least two years (Figure 4.5), with MRF_{DSI24} exhibiting larger drought intensity and later termination period (3-6 months) than MGR_{DSI24}. Correlation between MGR_{DSI24} and MRF_{DSI24} is larger than previous DSI calculations, although not significantly larger than DSI12.

4.4.3 Drought intensity (*DI*)

Table 4.4 shows the percentage of common drought months (CDM) at a given drought intensity (*i.e.*, percentile threshold exceedance) between $MGR_{DSI\text{-}n}$ and

$MRF_{DSI\text{-}n}$. The dry season has a greater percentage of CDM for all catchments (except Bedburn Beck and East Dart) across all DSI time scales and percentile thresholds. Highest percentage of CDM is shown at DSI24 and for the 55th percentile threshold exceedance (averaging 68-72 % and 70-75 %, respectively across catchments and seasons), whereas least percentage is shown at DSI3 and for the 95th percentile threshold exceedance (averaging 48-60 % and 48-58 %, respectively across catchments and seasons). The positive relationship between DSI time scale and percentage of CDM can be explained by the lower variability at longer DSIs due to the accumulation of river flow/rainfall deficits over longer periods.

To examine whether there is a lag effect on the percentage of CDM, the values of $MRF_{DSI\text{-}n}$ are shifted back by 1 to 6 months. Table 4.5, which gives the percentage of CDM at a given drought intensity between $MGR_{DSI\text{-}n}$ and the lagged $MRF_{DSI\text{-}n}$ for the Lambourn catchment, shows evidence of a lag effect as indicated by the improvement in the percentage of CDM relative to that of the unlagged version *i.e.*, lag 0. However, no clear pattern can be found as largest increment (*lagged minus lag 0*) in the percentage of CDM is shown at different lag times, percentile thresholds and DSI time scales. Large increases (difference between 16 and 23 percentage points) in the percentage of CDM during the dry season are shown for the following cases: lag 4 (DSI3, 95th percentile), lag 5 (DSI3, 95th percentile; DSI24, 95th and 90th percentiles) and lag 6 (DSI3, 95th percentile; DSI24, 95th and 90th percentiles). During the wet season, largest increases (difference between 30 and 46 percentage points) at lags 2 to 6 are shown for the

95th percentile at DSI24. Similar to the Lambourn, the Dove and Lud catchments (*see* Table A-1 and Table A-2 in Appendix A) show highest increases in the percentage of CDM at different lag times, DSI timecales and percentile thresholds, whereas all other catchments largely show either no or small increases (difference of less than 10 percentage points).

4.4.4 Frequency of drought months (*FDM*)

In the analysis of *FDM*, the use of the entire DSI-*n* time series (instead of the seasonal time series as in the case of *DI*) to determine the percentile threshold exceedance gives the opportunity to study the distribution of droughts over the two seasons. The histogram of *FDM* for each month, illustrated for the Lambourn catchment (Figure 4.6), shows a clear seasonal cycle, in particular at DSI3 and DSI6 at all percentile thresholds. Both MRF and MGR show contrasting patterns; for the MRF, the cycle shows with higher *FDM* during the wet season, whereas higher *FDM* is shown during the dry season for *FDM*.

Comparison between seasons shows lower *FDM* for MRF but higher for MGR during the dry season (Table 4.6a and Table 4.6b, respectively), with greatest difference generally shown for shorter duration DSIs and for lower percentile thresholds. Assessment of MGR against MRF shows predominantly underestimation of *FDM* by the former during the wet season but overestimation during the dry (Table 4.6c and Table 4.6d, respectively). For both seasons, the MGR generally displays least change for longer duration DSIs and lower percentile thresholds, whereas all other situations generally show comparable change magnitude.

4.4.5 Frequency of drought event at a given duration (*FDD*)

The difference in *FDD* for droughts with persistence of at least 3, 6, 10, and 12 months between $MGR_{DSI\text{-}n}$ and $MRF_{DSI\text{-}n}$ at different percentile exceedance thresholds is shown in Table 4.7. DSI_3 and DSI_{12} generally show, respectively, underestimation and overestimation in *FDD* by MGR. Large difference between MGR and MRF is generally shown for shorter duration DSIs, droughts with shorter persistence durations and/or lower percentile threshold exceedance. The number of cases showing small or no change is also significant. This is attributed to the fact that droughts with longer persistence duration, at a higher percentile exceedance threshold and/or longer duration DSI are rarer.

4.5 Discussion

4.5.1 Is the monthly gridded rainfall (MGR) a good proxy for catchment rainfall (CMR)?

There is good agreement between the time series of MGR and CMR as shown by the consistently very high (and statistically significant) correlation. However, the results may not be representative of other catchments as the magnitude of correlation largely rests on the density of station network which in turn influences the accuracy of the areal average and interpolation procedures used in the CMR and MGR, respectively. There is a decrease in the density of station network in the

UK from about 225 stations per 100 x 100 km^2 in the mid-1970s to about 140 stations per 100 x 100 km^2 in the early 2000s (Perry and Hollis, 2005). Catchments in mountainous regions generally have lower density of station network because of issues related to siting and exposure of raingauges, which in addition may also result in either under or overestimation of rainfall (Frei *et al.*, 2003).

4.5.2 Is the rainfall-based drought index ($MGR_{DSI\text{-}n}$) able to capture periods of low flows?

The $MGR_{DSI\text{-}n}$ has no difficulty in capturing most of the major hydrological drought events (*e.g.*, 1976, 1990-1992, 1995-1996, and 2006-2007). However, the intensity (and hence duration) of events simulated by the $MGR_{DSI\text{-}n}$ are underestimated, especially at longer duration DSIs (*e.g.*, DSI24). This is also reflected in Figure 4.7 showing the relationship between $MRF_{DSI\text{-}n}$ and $MGR_{DSI\text{-}n}$ in terms of the mean and maximum intensities for each major hydrological drought event, in which the underestimation in drought intensity by MGR is more apparent for maximum intensity, longer duration DSIs and bigger hydrological drought events (*i.e.*, $MRF_{DSI\text{-}n} > 50$).

The intensity of drought is related to the number of successive months with low rainfall (or flow); the greater the number of successive months with low rainfall (or flow), the greater the cumulative deficit hence the greater the intensity of the drought. The MGR has a lower number of successive months with low rainfall; resultantly the cumulative deficit is smaller hence lower drought intensity. The MRF has a higher number of successive months with low flow (hence higher intensity) because of the slower time taken for the river to reach its average flow state following rain events owing to catchment-controlled processes (*e.g.*, storage, recharge and runoff) and evaporative loss which exacerbate the drought signal. In the case where catchment characteristics contribute to the flashiness of the river, such as East Dart, the intensity between $MRF_{DSI\text{-}n}$ and $MGR_{DSI\text{-}n}$ is largely similar.

4.5.3 Can extreme (or moderate) droughts simulated by the rainfall-based index represent ($MGR_{DSI\text{-}n}$) correspondingly extreme (or moderate) drought conditions in river flow ($MRF_{DSI\text{-}n}$)?

Statistics of the three drought characteristics – *DI*, *FDM*, and *FDD* – conclude that in general, there is a better simulation of moderate hydrological drought events by the rainfall-based index ($MGR_{DSI\text{-}n}$) compared to extremes (in terms of drought intensity). Results from *DI* readily show highest percentage of common drought months between $MGR_{DSI\text{-}n}$ and $MRF_{DSI\text{-}n}$ for the 55th percentile exceedance threshold and lowest percentage for the 95th percentile. Better agreement between MGR and MRF for lower percentile threshold is also observed for *FDM* but only at DSI12/DSI24. This can be attributed to the fact that both MGR and MRF have DSI12/DSI24 droughts which persist over longer durations, in contrast with DSI3/DSI6 droughts which see longer persistence for MRF. For *FDD*, there is better agreement between MGR and MRF for higher percentile threshold exceedances as shown by the number of cases with small (±1 event) or no change. However, such cases are largely attributed to the difficulty in detecting the drought events, especially those with higher percentile threshold exceedance (*e.g.*, 95th percentile) and longer persistence duration (*e.g.*, at least 12 months), rather than the overestimation (or underestimation) of events by MGR.

4.5.4 What are the implications of varying the time scale of a drought index?

Varying the time scale of a drought index has the effect on the intensity and duration of droughts with longer DSI time scale producing greater intensity and longer duration of the drought event. Comparison between $MGR_{DSI\text{-}n}$ and $MRF_{DSI\text{-}n}$ illustrates the lag between meteorological and hydrological droughts which is apparent in several catchments under various drought conditions (*i.e.*, DSI time scales and percentile thresholds). The later occurrence (and termination) of hydrological droughts is due to catchment characteristics which result in the delayed progression and/or reduction of the amount of rainwater contributing to runoff through mainly groundwater storage and recharge.

Varying the time scale of a drought index can also achieve a better correlation between MGR and MRF. As shown in Table 4.3, the correlation between the datasets largely improves with higher DSI time scale. However, the correlation magnitude could be an artifact of the autocorrelation errors in both datasets. When the DSI time series have been corrected for autocorrelation, the correlation coefficients do not show significant difference across DSI time scales.

Shorter duration droughts are best represented using DSI with shorter time scales because of the nature of the algorithm at this time scale which terminates a drought easily. Longer duration droughts, on the other hand, are better represented using correspondingly longer duration DSIs because the rainfall (or river flow) deficits accumulate over a longer period. A shorter duration DSI (*e.g.,* DSI3) terminates easily resulting in frequent drought occurrences. This may be misleading as temporally adjacent minor droughts are often part of the same large drought event, rather than independent events, a problem known as mutually dependent droughts (Tallaksen, 2000). A longer duration DSI has the tendency to either smoothen short droughts or pool events into multi-year droughts lasting at least four years, thus overlooking the fact that all drought events are unique.

Detecting droughts in river flow is a complex affair as any threshold used to define anomalies in river flow may not be operationally suitable for the users of the river. For example, a given threshold may be critical from an ecological perspective, but not from a navigational point of view (Acreman and Adams, 1998). Any defined threshold, whether fixed or variable, serves specific aspects of the river's uses and any specified undoubtedly changes the characteristics of droughts. A drought may be longer or shorter in duration following shifts in thresholds (Paulo and Pereira, 2006). Such problem is eliminated in this study as droughts in river flow are expressed in the form of a drought index, consistent with meteorological droughts.

4.6 Conclusions

This study sets out to understand the credibility of using a rainfall-based drought index, the DSI, in the context of water resources management in which the DSI is applied to both monthly gridded rainfall (MGR) and monthly river flow (MRF) datasets to assess the consistency between meteorological ($MGR_{DSI\text{-}n}$) and hydrological (MRF_{DSI-n}) droughts in reproducing the temporal patterns and statistics of three drought characteristics: *DI*, *FDM*, and *FDD*. Examples from seven benchmark catchments are used to illustrate the objectives of this study.

In summary, this study has shown that:

- MGR is a good proxy for catchment rainfall. The MGR can therefore be considered a reliable dataset from which climate change experiments can be evaluated against;

- the DSI is able to capture periods of low flows. This can be seen in the ability of the MGR_{DSI-n} in capturing major drought events as simulated by the MRF_{DSI-n};

- the MGR_{DSI-n} generally represents moderate hydrological droughts better than extremes as shown by the smaller difference between MGR_{DSI-n} and MRF_{DSI-n} based on the statistics from the three drought characteristics; and

- there is a positive relationship between the time scale of DSI and the intensity (and duration) of the drought event it produces.

An overarching issue in this study relates to the underestimation of the drought intensity (and duration) by $MGR_{DSI-n.}$ This is unavoidable owing to catchment-controlled processes which contribute to the slower time taken for the river to reach its average flow state which in turn results in longer periods of low flow and subsequently the higher DSI intensity (and longer duration) for $MRF_{DSI\text{-}n}$. Future application of the DSI could explore the possibility of introducing, for example, a transfer function to adjust the intensity of $MGR_{DSI\text{-}n}$.

In conclusion, based on the results from the seven benchmark catchments, this study finds that the DSI is a credible index in estimating hydrological droughts, although the intensity and duration of droughts simulated by the DSI might be under-estimated. However, the close correlation between the rainfall and the hydrological DSI time series suggests changes and trends in rainfall-based DSI can provide useful inferences for understanding changes in future hydrological droughts, as well as meteorological drought. It is hoped that results from this study provide useful information when utilizing the DSI for assessment of drought impacts and future planning and management of water resources.

Table 4.1: Characteristics of the seven benchmark catchments. Source: www.ceh.ac.uk/data/nrfa

Catchment (station no.)	Area (km^2)	Altitude (m*)	Catchment description and factors affecting flows	Land cover (%)	Geology (%)
Bedburn Beck at Bedburn (24004)	74.9	Min: 109.0 Max: 532.6	• *Catchment description*: Predominantly upland catchment, on Millstone Grit in north and Coal Measures to south, with 25% drift cover of boulder clay and peat. Land use is upland moorland, grass pasture and coniferous forest; significant afforestation since gauge established. • *Factors affecting flows*: Natural to within 10% of the 95th percentile flow.	• Woodland (25.6); • Arable/horticultural (2.7); • Grassland (30.6); • Mountain/heath/bog (39.8); • Urban extent (0.1)	• Moderate permeability bedrock (82.1); • Generally low permeability superficial deposits (8.1); • Mixed permeability superficial deposits (15.9)
Beult at Stile Bridge (40005)	277.1	Min: 11.5 Max: 160.6	• *Catchment description*: Mainly Weald Clay (but includes some pervious sandstones). Rural (arable and grassland with significant woodland) with scattered settlements throughout the catchment. • *Factors affecting flows*: Runoff increased by effluent returns. Runoff reduced by industrial and/or agricultural abstraction.	• Woodland (15.0); • Arable/horticultural (40.5); • Grassland (35.9); • Urban extent (1.5)	• High permeability bedrock (11.8); • Moderate permeability bedrock (14.2); • Low permeability bedrock (73.9); • Generally high permeability superficial deposits (3.7); • Mixed permeability superficial deposits (3.0)

Dove at Izaak Walton (28046)	83.0	Min: 131.4 Max: 546.1	• *Catchment description*: Long narrow catchment. Upper reaches on Millstone Grit mudstone and sandstone. Western watershed is formed by a steep Carboniferous Limestone ridge. The Dove's passage across the Carboniferous Limestone is characterised by deep gorges (Wolfscote Dale, Dove Dale). Largely moorland. • *Factors affecting flows*: Natural to within 10% of the 95th percentile flow.	• Woodland (4.3); • Arable/horticultural (4.1); • Grassland (87.7) • Mountain/heath/bog (0.9); • Urban extent (0.4)	• Moderate permeability bedrock (100)
East Dart at Bellever (46005)	21.5	Min: 309.0 Max: 601.1	• *Catchment description*: Steep, very wet upland catchment, draining peat-covered Dartmoor Granite. Land use: moorland in the upper catchment, low grade agriculture and woodland in the lower. • *Factors affecting flows*: Natural to within 10% of the 95th percentile flow.	• Woodland (9.1); • Grassland (43.2) • Mountain/heath/bog (47.1)	• Generally low permeability superficial deposits (37.7)

Ellen at Bullgill (75017)	96.0	Min: 26.6 Max: 650.0	• *Catchment description*: Steep headwaters drain Uldale Fells and flow westward. Lower reaches follow the E-W trend of the Coal Measures with Carboniferous Limestone to the south. Extensively overlain by Boulder Clay with alluvium within the main river valley. • *Factors affecting flows*: Runoff reduced by public water supply abstraction. Runoff influenced by groundwater abstraction and/or recharge.	• Woodland (3.6); Arable/horticultural (11.1); • Grassland (82.0); Mountain/heath/bog (1.5); • Urban extent (0.6)	• High permeability bedrock (2.0); • Moderate permeability bedrock (56.1); • Low permeability bedrock (16.7); • Generally high permeability superficial deposits (0.6); • Mixed permeability superficial deposits (82.9)
Lambourn at Shaw (39019)	234.1	Min: 75.6 Max: 260.3	• *Catchment description*: Local suburban growth near gauging station but primarily a rural catchment (largely arable and grassland) developed on the Chalk of the Berkshire Downs (but significant Clay-with-Flints cover with alluvium in the valleys). • *Factors affecting flows*: Regulation from surface water and/or groundwater. Runoff influenced by groundwater abstraction and/or recharge.	• Woodland (10.3); • Arable/horticultural (53.8); • Grassland (30.2); • Mountain/heath/bog (0.1); • Urban extent (0.5)	• High permeability bedrock (97.3); • Generally high permeability superficial deposits (1.5); • Generally low permeability superficial deposits (30.2); • Mixed permeability superficial deposits (6.4)

Lud at Louth (29003)	55.2	Min: 15.4 Max: 153.0	• *Catchment description*: Catchment is predominantly (70%) Chalk, with around 30% superficial deposits, mainly Boulder Clay. Largely rural catchment with mainly arable farming, although there is urban development (Louth) just upstream of station. • *Factors affecting flows*: Runoff influenced by groundwater abstraction and/or recharge.	• Woodland (5.9); • Arable/horticultural (79.7); • Grassland (9.8) • Urban extent (2.2)	• High permeability bedrock (100.0); • Generally high permeability superficial deposits (1.0) • Mixed permeability superficial deposits (29.2)

* metres above ordnance datum

Table 4.2: Some statistics – correlation (*rho*), standard deviation (St.Dev.), mean absolute error (MAE) and mean absolute percentage error (MAE_p) – comparing monthly gridded (MGR) and catchment monthly (CMR) rainfalls for the seven catchments. *rho* values are statistically significant at the 90 % confidence level. B-B = Bedburn Beck; BEU = Beult; DOV = Dove; E-D = East Dart; ELL = Ellen; LAM = Lambourn; LUD = Lud

Catchment	*rho*	St.Dev. (CMR)	St.Dev. (MGR)	MAE	MAE_p
B-B	0.97	39.11	36.41	7.76	9.32
BEU	0.98	36.41	33.45	6.72	9.79
DOV	0.96	46.79	40.03	15.48	10.39
E-D	0.98	104.07	108.11	16.93	9.61
ELL	0.98	46.68	40.65	14.78	8.89
LAM	0.98	35.08	37.31	5.28	7.78
LUD	0.98	31.11	31.1	4.16	7.07

Table 4.3: Correlation (*rho1*) between monthly gridded rainfall (MGR) and monthly river flow (MRF) for DSI-*n* at the seven catchments. *rho2* refers to the correlation between MRF and MGR after correcting for autocorrelation in both datasets. All coefficient values are statistically significance at the 90 % confidence level. B-B = Bedburn Beck; BEU = Beult; DOV = Dove; E-D = East Dart; ELL = Ellen; LAM = Lambourn; LUD = Lud

	rho1				*rho2*			
	DSI3	DSI6	DSI12	DSI24	DSI3	DSI6	DSI12	DSI24
B-B	0.45	0.51	0.62	0.69	0.45	0.45	0.54	0.48
BEU	0.44	0.60	0.69	0.76	0.42	0.43	0.47	0.42
DOV	0.38	0.47	0.58	0.69	0.31	0.34	0.33	0.40
E-D	0.80	0.80	0.76	0.72	0.72	0.73	0.68	0.68
ELL	0.52	0.64	0.81	0.83	0.54	0.53	0.59	0.54
LAM	0.19	0.40	0.60	0.64	0.17	0.25	0.20	0.15
LUD	0.38	0.53	0.63	0.82	0.30	0.29	0.34	0.29

Table 4.4: Common drought months (CDM) between $MGR_{DSI\text{-}n}$ and $MRF_{DSI\text{-}n}$ at a given drought intensity (*DI*) during the (a) dry and (b) wet seasons. Data are expressed as percentage relative to $MRF_{DSI\text{-}n}$. B-B = Bedburn Beck; BEU = Beult; DOV = Dove; E-D = East Dart; ELL = Ellen; LAM = Lambourn; LUD = Lud. *p*>95, *p*>90, *p*>70, and *p*>55 indicate the 95th, 90th, 70th and 55th percentile threshold exceedance, respectively.

	DSI3				DSI6				DSI12				DSI24			
	p>95	*p*>90	*p*>70	*p*>55	*p*>95	*p*>90	*p*>70	*p*>55	*p*>95	*p*>90	*p*>70	*p*>55	*p*>95	*p*>90	*p*>70	*p*>55
(a) Dry season																
B-B	40.0	44.8	58.8	63.0	73.3	62.1	61.9	64.6	42.9	42.9	59.0	75.0	42.9	59.3	65.4	76.7
BEU	53.9	65.4	59.7	62.1	69.2	76.9	77.9	71.6	0.0	32.0	68.0	75.0	92.3	72.0	75.7	83.6
DOV	66.7	65.2	50.8	58.0	83.3	73.9	63.6	68.0	27.3	68.2	57.6	64.9	54.6	63.6	78.1	70.8
E-D	84.6	76.9	81.8	87.0	84.6	80.8	80.3	84.2	53.9	57.7	71.1	80.4	53.9	56.0	75.7	76.6
ELL	40.0	57.9	64.3	72.6	70.0	63.2	65.5	75.3	88.9	66.7	75.9	87.7	100.0	77.8	86.3	93.2
LAM	14.3	33.3	59.5	64.4	42.9	55.6	68.0	67.1	76.9	57.7	74.4	80.0	53.9	53.9	75.0	89.8
LUD	66.7	52.2	69.6	69.9	75.0	47.8	78.3	80.0	50.0	56.5	76.5	73.3	36.4	86.4	86.4	92.1
(b) Wet season																
B-B	33.3	48.3	63.5	57.5	42.9	53.6	71.4	73.8	21.4	42.9	65.5	76.2	64.3	46.4	78.1	78.1
BEU	23.1	34.6	59.7	62.6	46.2	53.9	65.8	77.9	15.4	38.5	79.0	77.9	69.2	72.0	73.0	81.1
DOV	50.0	47.8	47.1	53.5	50.0	69.6	62.7	55.0	54.6	77.3	65.2	63.6	63.6	63.6	75.0	65.3
E-D	69.2	69.2	81.8	75.9	84.6	80.8	83.1	84.4	61.5	52.0	81.3	86.1	61.5	72.0	71.6	76.4
ELL	40.0	42.1	56.4	52.1	60.0	73.7	83.6	74.4	88.9	66.7	75.9	86.8	88.9	83.3	75.0	91.4
LAM	0.0	7.4	41.8	49.6	23.1	26.9	50.0	61.5	57.1	37.0	63.3	67.8	23.1	46.2	66.2	68.0
LUD	50.0	47.8	47.8	56.7	50.0	30.4	47.8	59.2	33.3	56.5	70.6	78.4	36.4	63.6	75.8	85.9

Table 4.5: As Table 4.4, but between $MGR_{DSI\text{-}n}$ and lagged $MRF_{DSI\text{-}n}$ for the Lambourn catchment during the (a) dry and (b) wet seasons. Values greater than lag 0 are underlined. *p*>95, *p*>90, *p*>70, and *p*>55 indicate the 95th, 90th, 70th and 55th percentile threshold exceedance, respectively.

	DSI3				DSI6				DSI12				DSI24			
	p>95	*p*>90	*p*>70	*p*>55	*p*>95	*p*>90	*p*>70	*p*>55	*p*>95	*p*>90	*p*>70	*p*>55	*p*>95	*p*>90	*p*>70	*p*>55
(a) Dry season																
Lag 0	14.3	33.3	59.5	64.4	42.9	55.6	68.0	67.1	76.9	57.7	74.4	80.0	53.9	53.9	75.0	89.8
Lag 1	21.4	37.0	64.6	67.5	35.7	66.7	75.6	80.7	69.2	61.5	75.3	79.8	53.9	60.0	80.0	92.0
Lag 2	28.6	37.0	59.5	63.3	35.7	63.0	71.8	78.4	61.5	65.4	77.9	80.7	53.9	64.0	84.0	93.0
Lag 3	23.1	42.3	53.9	54.7	23.1	53.9	68.0	77.3	46.2	65.4	79.2	82.5	61.5	68.0	82.7	90.6
Lag 4	30.8	46.2	44.9	50.4	23.1	50.0	60.3	69.3	46.2	61.5	77.6	80.7	69.2	68.0	81.3	86.9
Lag 5	30.8	38.5	38.5	48.7	15.4	38.5	50.0	60.2	30.8	53.9	71.1	74.3	76.9	72.0	79.7	80.7
Lag 6	30.8	30.8	41.0	48.3	0.0	23.1	44.9	60.2	23.1	46.2	65.8	66.1	76.9	72.0	74.3	75.6
(b) Wet season																
Lag 0	0.0	7.4	41.8	49.6	23.1	26.9	50.0	61.5	57.1	37.0	63.3	67.8	23.1	46.2	66.2	68.0
Lag 1	0.0	11.1	46.8	55.9	30.8	34.6	59.0	69.2	69.2	46.2	69.2	71.9	38.5	50.0	72.7	75.5
Lag 2	0.0	11.1	54.4	61.0	30.8	46.2	68.0	73.5	76.9	50.0	76.9	73.5	53.9	53.9	77.6	78.2
Lag 3	0.0	11.5	55.1	59.0	30.8	46.2	70.5	71.6	84.6	53.9	80.8	75.0	61.5	57.7	80.3	80.0
Lag 4	15.4	15.4	50.0	55.6	23.1	50.0	70.1	69.0	76.9	61.5	75.6	76.6	69.2	61.5	80.3	82.8
Lag 5	15.4	26.9	44.9	50.4	23.1	42.3	63.6	63.5	61.5	57.7	67.5	71.2	69.2	68.0	77.3	80.6
Lag 6	23.1	34.6	41.0	48.3	23.1	38.5	61.0	60.0	61.5	57.7	62.3	64.9	61.5	72.0	74.7	79.4

Table 4.6: Frequency of drought months (*FDM*) at a given DSI time scale (DSI-*n*) and intensity. Seasonal difference, expressed as absolute values, is shown for (a) MRF and (b) MGR. Percentage change in *FDM* exhibited by MGR, relative to MRF, is given in (c) and (d) during the dry and wet seasons, respectively. B-B = Bedburn Beck; BEU = Beult; DOV = Dove; E-D = East Dart; ELL = Ellen; LAM = Lambourn; LUD = Lud. *p*>95, *p*>90, *p*>70, and *p*>55 indicate the 95th, 90th, 70th and 55th percentile threshold exceedance, respectively.

	DSI3				DSI6				DSI12				DSI24			
	p>95	*p*>90	*p*>70	*p*>55	*p*>95	*p*>90	*p*>70	*p*>55	*p*>95	*p*>90	*p*>70	*p*>55	*p*>95	*p*>90	*p*>70	*p*>55
(a) MRF (*dry minus wet*)																
B-B	-17	-43	-61	-8	-4	-28	-90	-88	0	-8	-21	4	-2	-5	-21	-12
BEU	-2	-26	-84	-42	-12	-7	-63	-85	2	1	-15	14	1	-5	-19	-1
DOV	1	-21	-64	-25	-11	-9	-73	-82	-8	-6	-22	6	-16	-15	-22	4
E-D	-12	-31	-27	22	-10	-27	-61	-55	-14	-21	-1	22	-11	-17	-9	3
ELL	-7	-21	-19	28	-7	-21	-34	-23	0	-4	2	12	0	-7	-2	3
LAM	-7	-17	-45	-118	-3	-19	-24	-86	-8	-10	-20	0	-4	-3	-21	-15
LUD	-5	-10	-28	-81	-5	-6	-19	-65	1	-5	1	-13	-8	-4	-14	-11
(b) MGR (*dry minus wet*)																
B-B	1	3	39	72	0	-2	6	35	2	-4	13	7	2	1	-7	-14
BEU	6	10	44	66	8	9	11	35	-2	5	7	26	7	11	-11	8
DOV	-7	3	46	53	3	-3	17	37	-2	2	22	12	4	-1	16	3
E-D	-10	-11	29	76	-8	-19	-9	1	-8	-8	21	16	1	-5	3	4
ELL	3	9	55	84	-3	-5	15	51	2	10	18	12	0	1	19	3
LAM	-3	3	32	52	7	9	-12	14	4	-2	8	10	4	-5	7	2
LUD	-1	-4	30	37	5	10	9	21	7	1	-1	3	4	4	-2	-4

(c) Dry season																
B-B	150.0	328.6	92.6	32.5	16.7	92.9	123.1	74.4	7.1	8.3	23.3	-1.6	15.4	12.0	9.9	-2.6
BEU	33.3	138.5	182.9	57.4	142.9	36.4	82.2	83.3	-14.3	7.7	16.2	5.0	23.1	36.4	6.3	2.7
DOV	-33.3	100.0	157.1	44.3	116.7	16.7	150.0	84.7	42.9	21.1	40.0	-8.5	333.3	50.0	35.8	-15.3
E-D	14.3	100.0	44.4	21.4	12.5	33.3	56.5	32.2	50.0	40.0	14.7	-4.0	85.7	37.5	8.7	-7.1
ELL	83.3	187.5	80.4	28.9	33.3	100.0	63.2	52.1	11.1	43.8	14.5	0.0	0.0	28.6	21.6	9.6
LAM	20.0	55.6	66.7	141.7	41.7	82.4	9.0	66.7	66.7	19.0	20.6	6.1	36.4	-4.2	21.2	20.5
LUD	22.2	16.7	52.7	93.7	55.6	40.0	23.7	61.4	25.0	15.0	-1.5	8.4	85.7	20.0	10.2	9.0
(d) Wet season																
B-B	-39.1	-46.0	-43.5	-30.5	-12.5	-31.0	-37.2	-36.5	-7.1	-6.3	-18.1	-4.1	-13.3	-10.0	-7.6	-0.8
BEU	-28.6	-46.2	-53.8	-39.7	-52.6	-27.6	-34.3	-38.2	16.7	-8.0	-13.3	-5.7	-25.0	-29.6	-4.8	-5.4
DOV	36.4	-36.4	-55.6	-34.5	-41.2	-11.1	-43.7	-48.9	-20.0	-16.0	-28.6	-15.9	-52.6	-24.1	-25.3	-14.9
E-D	-5.3	-24.4	-31.1	-26.0	-5.6	-10.3	-24.3	-19.7	-15.0	-19.4	-14.5	1.0	-33.3	-18.2	-7.7	-8.3
ELL	-38.5	-51.7	-56.9	-40.6	-15.4	-27.6	-34.7	-39.4	-11.1	-35.0	-15.1	0.0	0.0	-19.0	-18.9	10.0
LAM	-11.8	-28.6	-38.2	-47.8	-33.3	-38.9	-6.6	-31.1	-35.3	-12.9	-15.9	-2.6	-26.7	3.7	-16.1	1.0
LUD	-14.3	-10.7	-34.9	-41.0	-35.7	-30.8	-17.9	-31.9	-27.3	-12.0	1.5	-7.4	-40.0	-16.7	-8.2	1.0

Table 4.7: Difference in frequency of droughts at a given duration (*FDD*) for droughts with persistence of at least 3, 6, 10 and 12 months ($m \geq 3$, $m \geq 6$, $m \geq 10$ and $m \geq 12$, respectively) at a given percentile threshold between MGR and MRF for (a) DSI3, (b) DSI6, (c) DSI12 and (d) DSI24. Data are expressed as absolute values; B-B = Bedburn Beck; BEU = Beult; DOV = Dove; E-D = East Dart; ELL = Ellen; LAM = Lambourn; LUD = Lud. $p>95$, $p>90$, $p>70$, and $p>55$ indicate the 95th, 90th, 70th and 55th percentile threshold exceedance, respectively.

	$p>95$				$p>90$				$p>70$				$p>55$			
	$m\geq3$	$m\geq6$	$m\geq10$	$m\geq12$	$m\geq3$	$m\geq6$	$m\geq10$	$m\geq12$	$m\geq3$	$m\geq6$	$m\geq10$	$m\geq12$	$m\geq3$	$m\geq6$	$m\geq10$	$m\geq12$
(a) DSI3																
B-B	1	0	-1	0	-1	3	-1	-1	2	-3	0	-1	4	-6	0	-1
BEU	1	-2	-1	0	1	1	-1	0	-4	3	-1	-2	-2	2	2	-1
DOV	0	-1	-1	0	2	0	-1	-1	-2	2	0	-1	1	-2	1	-1
E-D	-2	0	0	0	0	1	0	0	-3	2	0	0	-3	-1	1	0
ELL	1	-1	-1	-1	2	-1	-1	-1	-3	3	-1	-1	-3	2	2	-1
LAM	0	0	-1	0	4	-1	-2	-2	13	-1	-6	-7	12	1	-4	-7
LUD	0	0	0	0	2	-1	-1	-1	6	6	-1	-4	6	7	2	-3
(b) DSI6																
B-B	1	1	-1	-1	0	2	1	-1	-6	-3	1	0	-6	-3	4	4
BEU	-1	2	-1	0	1	0	-1	-1	3	3	-2	-1	2	3	-1	-2
DOV	0	1	0	0	0	0	0	0	-2	-1	1	1	-5	-1	0	1
E-D	-1	0	0	0	-2	0	0	0	-5	1	1	0	-4	-2	3	0
ELL	-1	0	0	0	2	-1	0	0	-6	2	0	0	-6	-1	3	0
LAM	-1	0	-2	-1	2	-1	0	-1	5	4	-1	-2	5	2	2	0
LUD	2	0	0	0	2	0	-1	0	4	2	1	1	3	4	2	1

(c) DSI12

B-B	0	0	0	-1	4	4	2	1	0	1	2	1	4	0	0	0
BEU	1	0	0	0	4	1	-1	-1	1	2	3	0	1	-1	1	2
DOV	0	0	1	1	1	0	0	-1	1	1	0	0	0	-2	-2	-3
E-D	0	0	1	1	-4	2	0	0	1	-3	0	-1	0	-1	-2	-1
ELL	0	0	0	0	-2	0	0	0	1	-3	-2	-1	2	1	1	0
LAM	1	0	0	0	0	-1	-1	0	3	0	1	0	11	4	-1	0
LUD	1	0	0	0	-1	0	0	1	0	0	-1	0	4	-1	0	0

(d) DSI24

B-B	2	0	0	0	1	1	1	1	-3	1	1	1	-1	-2	0	1
BEU	0	0	-1	0	2	0	-1	-1	-2	-1	1	1	-1	-3	2	2
DOV	-2	0	0	0	-1	-2	1	1	-2	1	0	0	-1	-3	-3	-2
E-D	-1	2	-1	0	-1	-1	2	0	-7	-2	0	0	-7	-6	-1	-1
ELL	0	0	0	0	-1	0	0	0	-3	-1	0	0	0	-2	0	0
LAM	-1	1	0	0	0	0	-1	1	3	2	1	0	7	0	0	0
LUD	1	-1	0	-1	1	1	1	0	1	0	0	0	3	0	0	0

Figure 4.1: Approximate locations of the seven benchmark catchments used in the study. Map source: Jenkins *et al*. (2009)

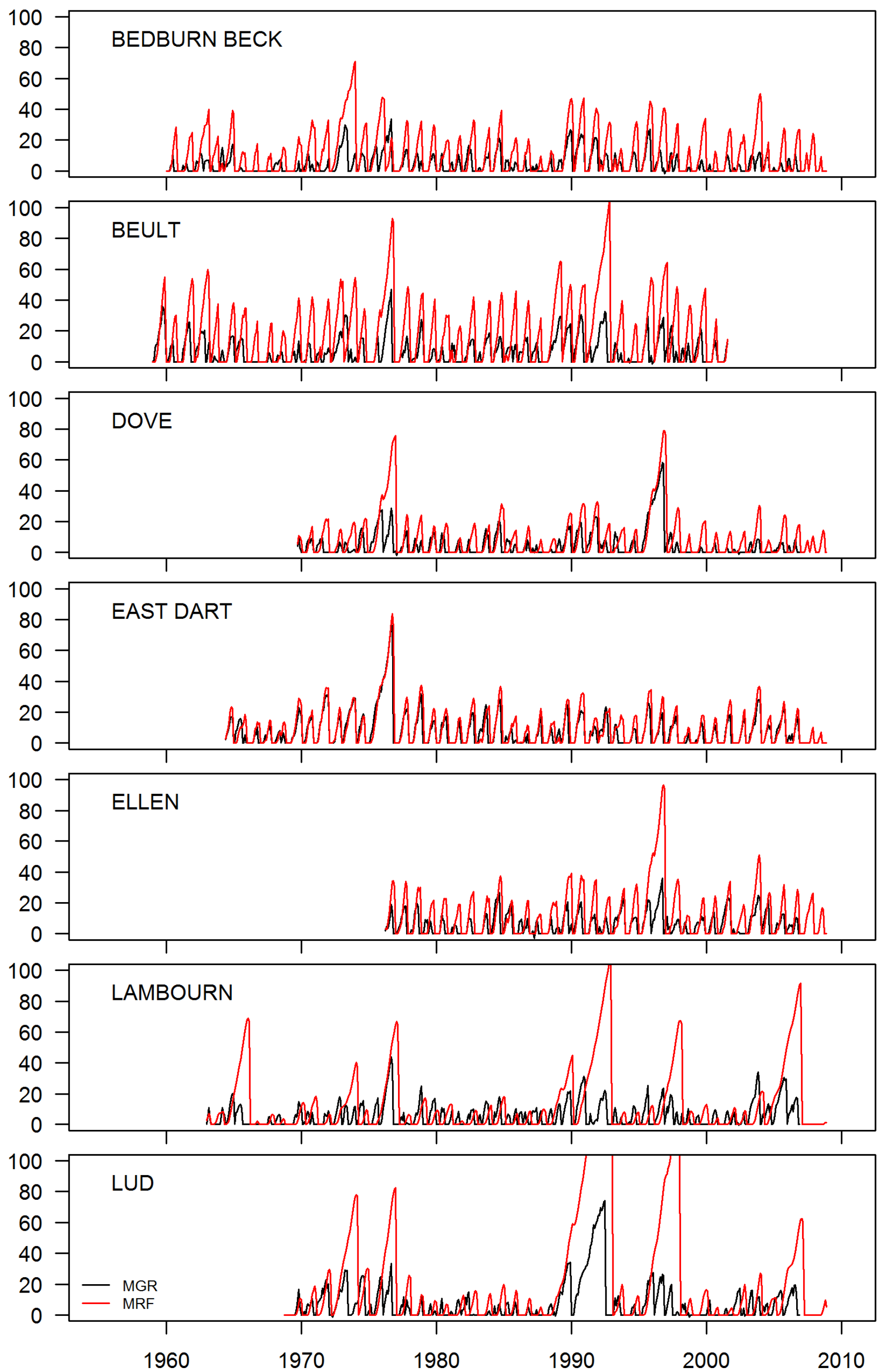

Figure 4.2: Time series of DSI3 as simulated by monthly gridded rainfall (MGR) and monthly river flow (MRF) for the seven benchmark catchments. *y*-axis shows the DSI intensity.

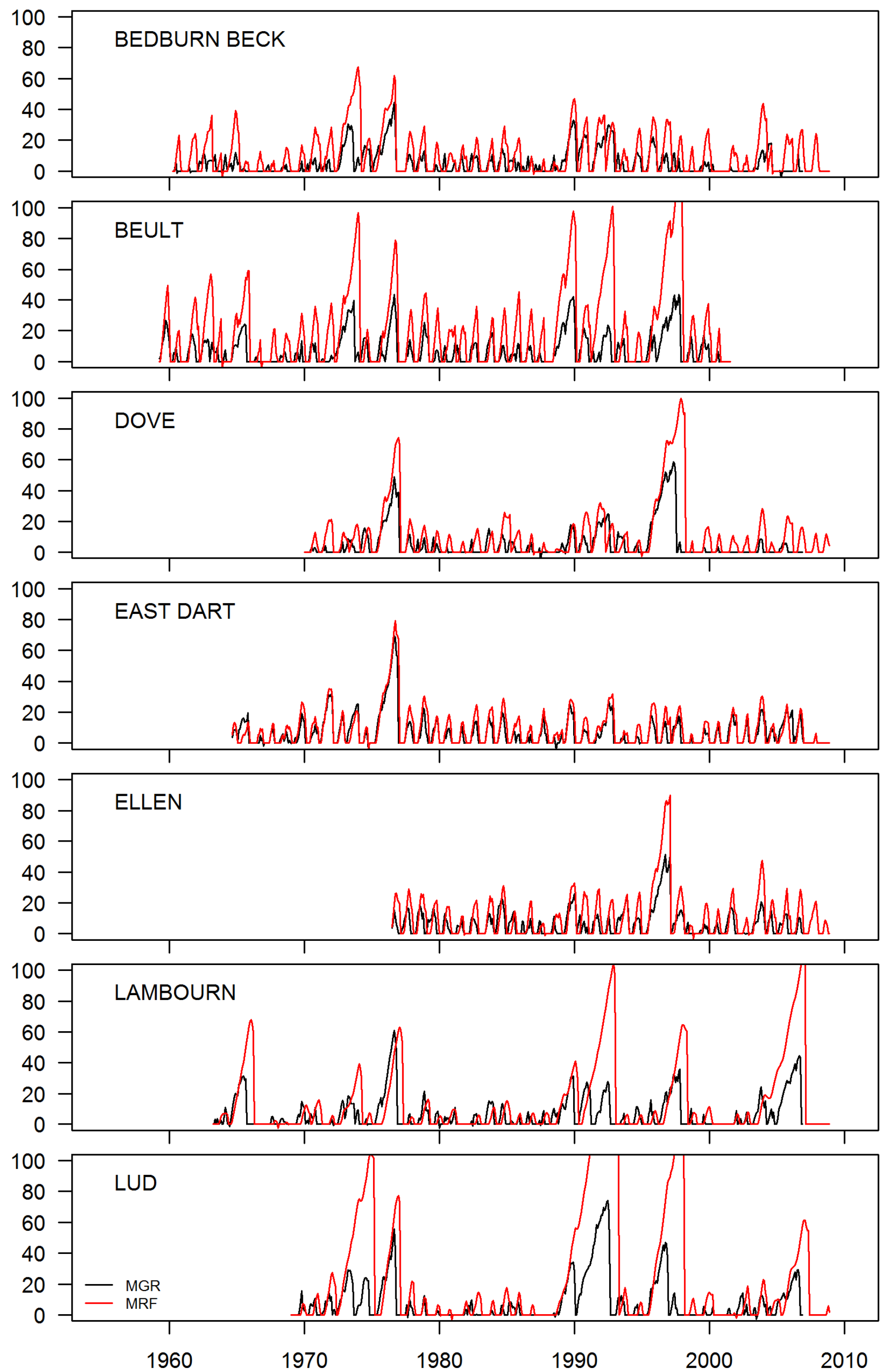

Figure 4.3: As Figure 4.2, but for DSI6.

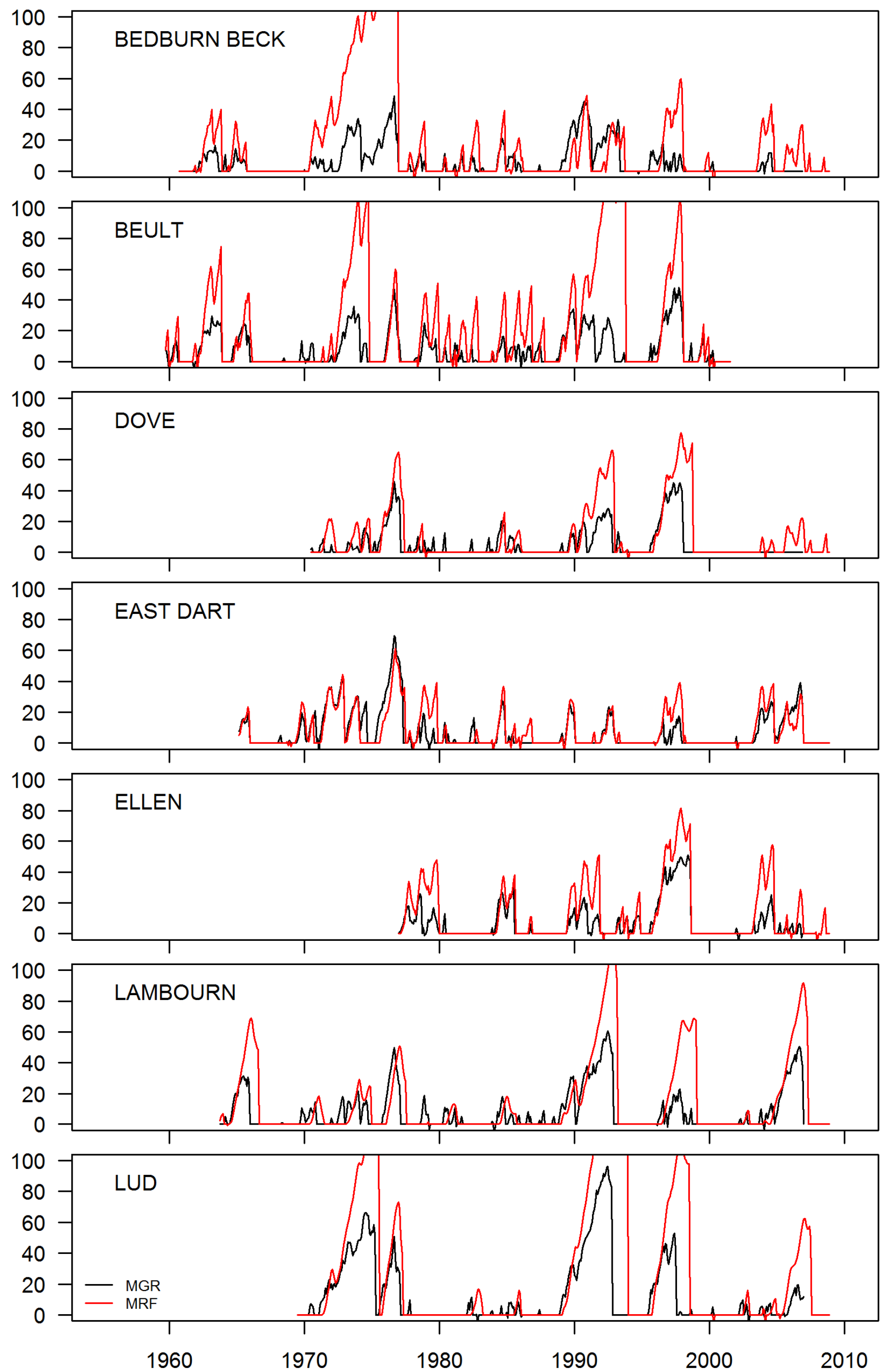

Figure 4.4: As Figure 4.2, but for DSI12.

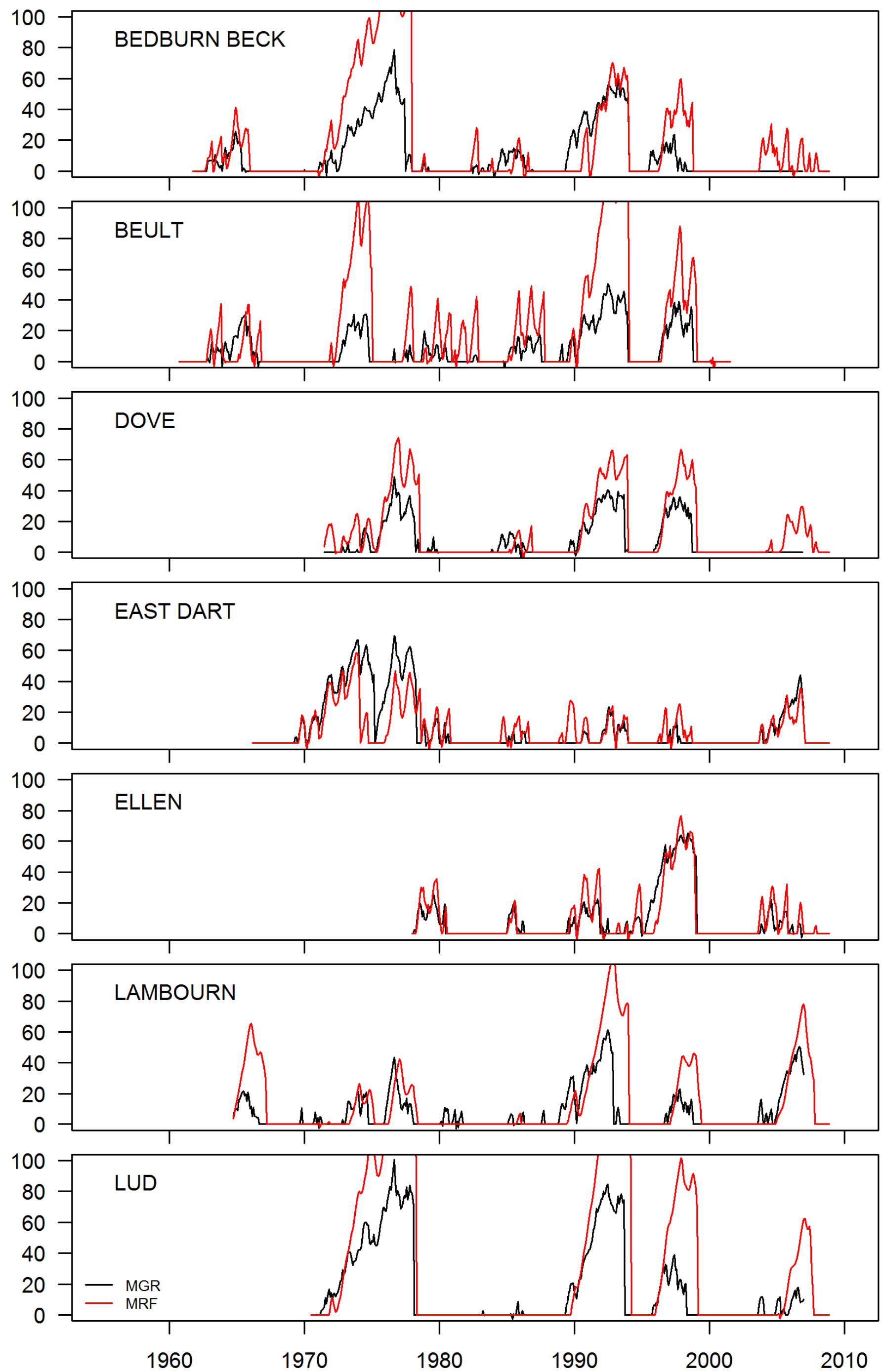

Figure 4.5: As Figure 4.2, but for DSI24.

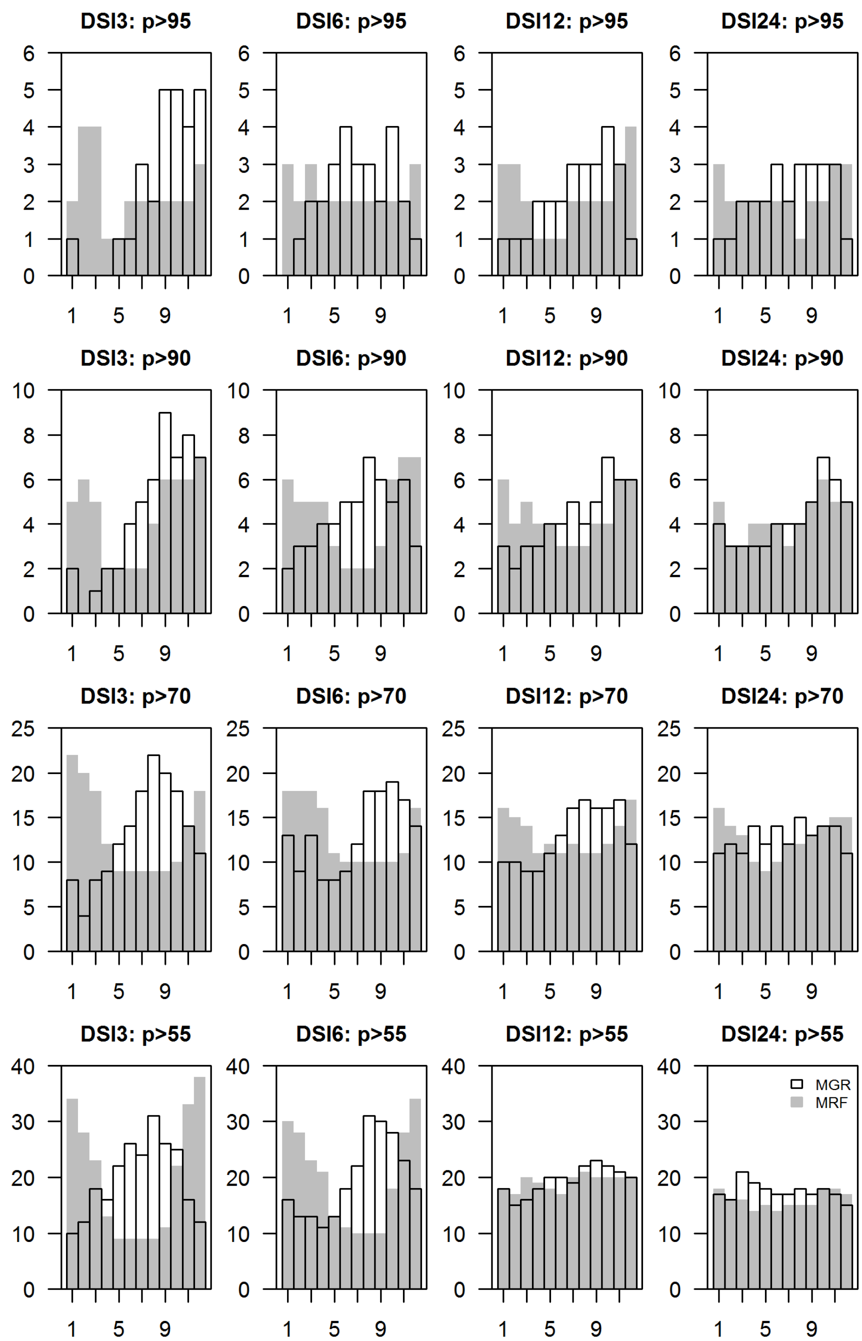

Figure 4.6: Histogram of the frequency of drought months (*FDM*) at a given DSI time scale and percentile threshold exceedance for the Lambourn catchment. *p*>95, *p*>90, *p*>70, and *p*>55 indicate the 95th, 90th, 70th and 55th percentile threshold exceedance, respectively. *x*-axis shows the month numbers. MGR = monthly gridded rainfall; MRF = monthly river flow.

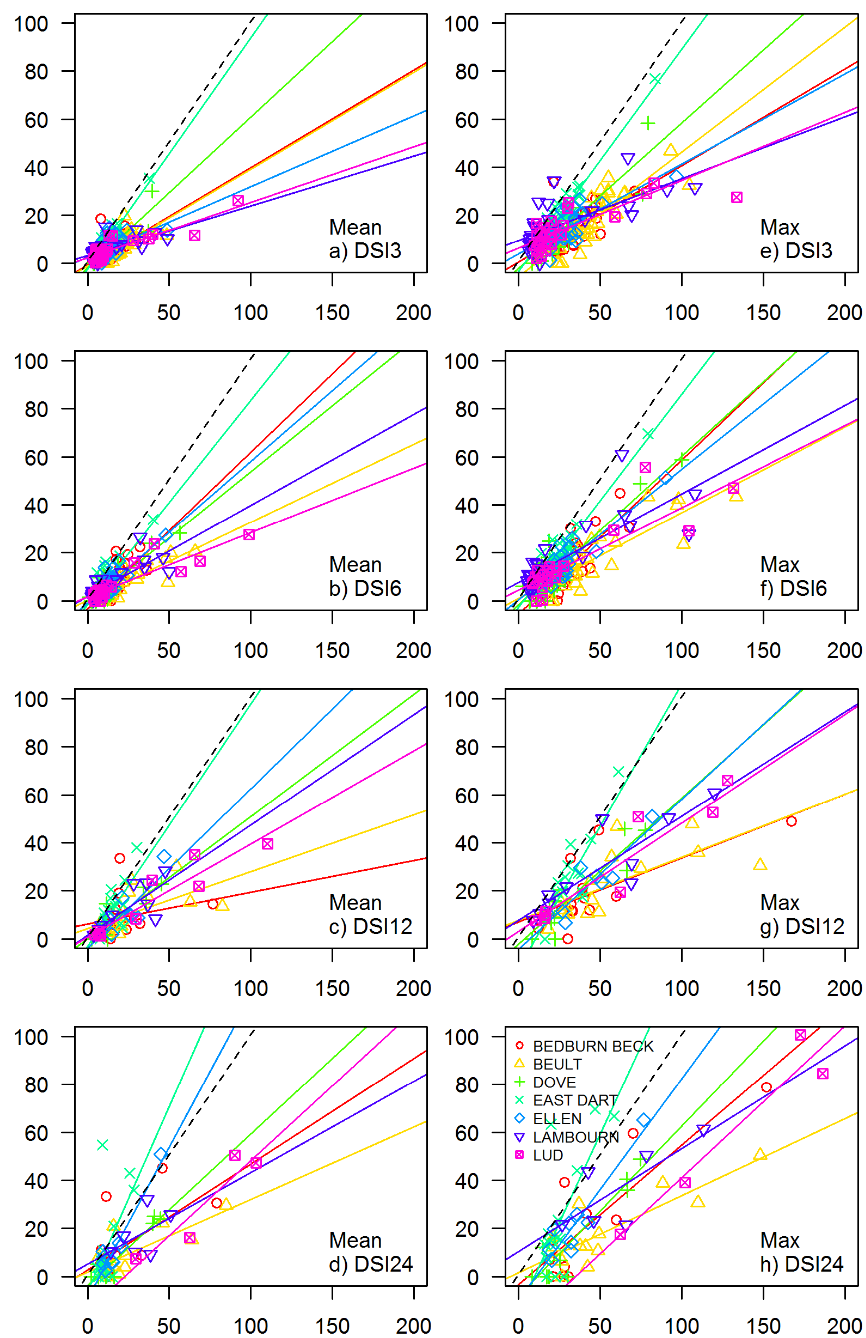

Figure 4.7: Relationship between $MRF_{DSI\text{-}n}$ and $MGR_{DSI\text{-}n}$ in terms of the mean and maximum intensities during each major hydrological drought event. *x* and *y* axes show the DSI intensities for MRF and MGR, respectively.

Chapter 5

Spatial Coherence of Meteorological Droughts in the UK since 1914

Abstract

This chapter is based on the following paper published in *Area*:

Rahiz M and New M (2012) Spatial coherence of meteorological droughts in the UK since 1914. *Area*, 44: 400-410. DOI: 10.1111/j.1475-4762.2012.01131.x

This chapter addresses the second objective of the thesis: "*To examine the spatial coherence of droughts from the recent past*". The rationale for this section of the thesis is to understand the historical climatology of droughts in the UK in terms of their coherence so that better assessment of regional drought risk can be made in light of future climate change.

The drought severity index (DSI) is applied on a 3-, 6-, 12- and 15-month time scales to the UKMO monthly gridded precipitation dataset to study the spatial coherence of meteorological droughts in the UK from 1914 to 2006. Analyses are undertaken for the wet (October–March) and dry (April–September) seasons, and under moderate and extreme drought severities. A drought covariance index is developed to quantify the spatial coherence of droughts based on the fraction of years with extreme (or moderate) droughts that each pair of grid points has in common.

Results show that over the course of the 93 year period, large parts of the

domain are coherent at least 60 % of the time under moderate drought conditions. The case for extreme drought conditions, on the other hand, showed lower coherence (20-50 % of the time) across large parts of the UK. A difference in the magnitude of coherence between the dry and the wet seasons was also evident, with the wet season generally showing greater coherence. The study also showed high coherence characterizing large areas in east and southeast England, areas which are already known to be drought-stressed. Results are discussed in terms of the relationship between the North Atlantic Oscillation and precipitation, the spatial variability of precipitation and the detectability of droughts. Finally, the implications of the study for drought management with focus on water transfers are examined.

There are several significant aspects from the results of this study. First, it provides an understanding of regional drought risk in the UK from a climatological perspective so that better management decisions can be implemented. Second, it presents an opportunity to explore the implementation of water transfers as a form of risk management. Third, it provides a basis for climate model evaluation, which in turn could provide information on the reliability of model projections.

5.1 Introduction

It is well accepted that the climate is changing. Research into climatic trends has shown that from 1906 to 2005, the average global surface temperature has increased by 0.74 °C, rising at a rate of 0.13 °C per decade (IPCC, 2007). Of most importance to many sectors is the trend of precipitation and its spatial distribution, which potentially has major consequences for ecological, economic, infrastructural and societal systems (Beniston *et al*., 2007; Mishra and Singh, 2010). One key area where precipitation anomalies have the greatest impact is on droughts, which are widely recognised as extreme climate events (Dai, 2011).

Drought research covers many spatial scales. On a global scale, Dai *et al*. (2004) showed that from 1900 to 2008, the trend of global drought displayed patterns of drying over Africa, south and southeast Asia, eastern Australia, northern America, southern Europe and most of Alaska and western Canada. Burke *et al*. (2006) observed a drying trend since 1952, with droughts being slightly less frequent but longer in duration. This conclusion was not shared by Bordi *et al*. (2006), who found that global drought trends from 1958 to 2001 were progressing towards wetter conditions. The difference in conclusions, nonetheless, could arise from the different datasets used.

On the European scale, a rich database of drought research is available. In a study of European droughts from 1901 to 2006, Lloyd-Hughes (2012) showed that spatially extensive, sustained droughts are a result of the combination of multiple smaller-scale, short-duration events. Lloyd-Hughes and Saunders (2002) presented a high spatial resolution and multi-temporal climatology for 20th century European droughts in which they concluded that the trends of extreme and/or moderate drought conditions changed insignificantly. Briffa *et al*. (2009), on the other hand, showed a trend towards more frequently occurring dry summers.

Focusing on a smaller region, the UK has seen several drought studies.

Bryant *et al*. (1994) gave an analysis of the 1988–1992 drought in the context of long-duration droughts (1850–1992) using monthly observed and synthetic river flow data, and found that droughts were more extreme in eastern and southern England, although they did not last more than four years. The development of the 1988–1992 drought was documented by Marsh *et al*. (1994), in which they attributed the event to the combination of unusual weather systems and abnormally high temperatures. Phillips and McGregor (1998) examined drought conditions from 1962 to 1995 over southwest England and observed a high degree of spatial coherence (in terms of duration) for the 1992 drought, but not for the 1983–1984 event, which saw considerable variability within the study area. For the 2004–2006 drought event, Marsh *et al*. (2008) observed similar spatial disparity, with severe rainfall deficiencies over southeast and southwest England. The droughts of 1995–1996 showed patterns of spatial division as well. However, the focus of the drought was on northern England (Walker and Smithers, 1998). Within a regional context, there exists appreciable local variation. This was also shown in the study by Marsh (2007) of the 2004–2006 drought, which saw maximum rainfall deficiencies exceeding 25 % over southern Britain. Fowler and Kilsby (2002a) compared the behaviour of droughts from 1881 to 1998 at five sites in Yorkshire, and concluded that drought events in Yorkshire were spatially variable.

5.2 Research aim

Although droughts have been widely documented in terms of their progression, most of the original research has a strong regional focus (Table 5.1). This is probably related to the nature of droughts, which affects certain regions more than others. In addition, these studies focus on selected drought events (*e.g.*, 1988–1992 and 2004–2006) and not the entire spectrum of the available historical record (Marsh *et al*., 2007). This hinders our understanding of the variability or evolution of droughts (Wade *et al*., 2007). To the authors' knowledge, there is no study that compares the characteristics of droughts between seasons – a seemingly tricky affair because droughts often straddle seasons that nonetheless would provide useful insights into the seasonal variability of events.

The aim of this study is to document the characteristics of droughts in the UK by examining their climatology from 1914 to 2006 in terms of the magnitude and extent of coherence. This aspect of drought characteristics has been considered briefly in the literature (*e.g.*, Phillips and McGregor 1998; Burke *et al*., 2010; Hannaford *et al*., 2011) and as such deserves greater in-depth investigation. This study focuses on meteorological drought rather than other forms of drought (*e.g.*, hydrological) primarily because of the availability of more meteorological data than river flow data, which allows the patterns of droughts for the whole of the UK to be studied. The methodology adopted in this study contrasts with other studies in that a drought index is applied on a gridded basis across the whole of the UK as opposed to few locations or selected regions (*e.g.*, Fowler and Kilsby, 2002a). In addition, the seasonal characteristics of droughts are investigated.

The rationale of this study is two-fold. First, it provides an understanding of regional drought risk in the UK so that better management strategies can be implemented. Second, it presents a basis for climate model evaluation, which in turn could provide information on the reliability of model projections.

5.3 Methodology

5.3.1 Data

The 5 x 5 km monthly gridded rainfall dataset from 1914 to 2006 (Perry and Hollis, 2005) covering the whole of the UK is used. The dataset is then regridded to a 0.225° resolution (approximately 25 km) to retain consistency in resolution for the authors' future work of comparing historical droughts with those generated from the UKCP09 regional climate model simulations.

5.3.2 Drought severity index

The drought severity index (DSI) (Phillips and McGregor, 1998) is then applied to the entire time series of each grid point. The DSI is a rainfall-based drought index that describes the cumulative precipitation anomaly for a given location on an *n* month time scale, where *n* is typically 3, 6 and 12 months. The following describes the DSI algorithm, using the example of a 3-month DSI (DSI3) (after Phillips and McGregor, 1998).

Consider the rainfall anomaly in month t, denoted X_t. If X_t is negative (*i.e.*, below its mean level) and rainfall in the 3-month period, X_t , X_{t-1} , X_{t-2} , is lower than its 3-monthly mean, then initiate a drought sequence in month t, assigning the DSI a positive value that is equal to the precipitation deficit in month t.

Now consider the month t + 1. Suppose the rainfall anomalies in months t and t + 1 were –X mm and –Y mm, respectively, then the DSI3 for month t + 1 equals $X + Y$, if and only if the 3-monthly mean total for the months t - 1, t and t + 1 has not been exceeded. If the rainfall anomaly is positive in month t + 1, then a drought can continue, with DSI3 = X - Y, provided that the 3-monthly mean total has not been exceeded. All drought sequences are terminated immediately when this 3-monthly mean total has been exceeded and DSI3 is assigned a value of zero.

To allow for comparison between locations, the index is standardized by dividing the DSI3 values by the location's mean annual rainfall and then multiplying by 100. The final index value will thus express the accumulated precipitation deficit as a percentage of the mean annual rainfall of the location. The calculation of DSI at other time scales follows the same principle as shown for DSI3, but using an n month accumulation and mean. As an illustration, the DSI3 value for March 2002 would be the cumulative precipitation anomalies from January–March 2002. Likewise, the DSI12 value for April 2002 would be the precipitation anomalies accumulated from May 2001 to April 2002.

In this study, calculation of precipitation anomalies was with respect to the monthly mean of 1961–1990 time period. In addition, a 3-, 4-, 12- and 15-month DSI (DSI3, DSI6, DSI12, and DSI15, respectively) are used to investigate the temporal and spatial patterns of droughts at different time scales.

5.3.3 Seasonal disaggregation

Next, the DSI time series are separated into dry and wet seasons covering the months of April–September and October–March, respectively. The classification is based on the UK hydrological year and therefore reflects the hydrological variability in terms of storage (*e.g.*, groundwater recharge) and loss (*e.g.*, evaporation). This is more meaningful in the context of water resources management and planning as opposed to the conventional climatological seasonal classes, *i.e.*, December–January–February, March–April–May, June–July–August and September–October–November. The seasonal disaggregated datasets would therefore comprise the DSI values for the months of April–September (for the dry season) and October–March (for the wet season) of each year from 1914 to 2006.

5.3.4 Drought covariance index

From a water resources perspective, spatially extensive droughts can be particularly damaging because water deficits in one part of a catchment or operating region cannot be compensated in other parts. Therefore a drought covariance index is developed to allow the spatial coherence of drought events to be quantified. At each grid point, for a given DSI series, extreme and moderate drought years are defined as those that exceed the 90th and 70th percentiles of the entire seasonal DSI time series (note that subscripts 70 and 90 are used hereafter as notations to represent moderate and extreme droughts respectively). Then calculated is the fraction of years, f, with extreme (or moderate) droughts that each pair of grid points has in common. For example, f_{90} of 0.5 and f_{70} of 0.8 indicate that two grid points have 50 % and 80 % of extreme and moderate drought years in common. This is illustrated in Figure 5.1, which shows the *f* values between the grid point containing the Lambourn catchment in southern England and all other grid points in the UK. For this location, more generally for all UK locations, the *f* value is highest and more widespread during the wet season, and for shorter duration droughts, and lower and less widespread during the dry season, and for longer duration droughts.

For each grid point, the covariance index, CI_{90} and CI_{70}, was calculated as the average of all pairwise *f* values for that grid point. This provides a coarse measure of the spatial patterns of drought covariance across the UK.

A limitation of the drought covariance index relates to the geographical and directional biases which affect primarily peripheral locations such as coastal sites. The limited land area surrounding these locations means that such locations will inevitably have a smaller extent of area with high *f* values (given also that the calculation of the *f* value is based on land areas only). Consequently, this will affect the final aggregated value of the covariance index.

5.3.5 Spatial coherence decay

Finally, the spatial coherence decay (*SCD*) of extreme and moderate droughts is quantified using a concept similar to the correlation decay distance (Hofstra and New, 2009). For a given grid point, the fraction of grid points within a given distance that has an *f* value greater than a given threshold (*e.g.*, $f \geq 0.8$) is calculated. Thus $SCD_{90}^{0.8}$ of 0.5 within 100 km indicates that 50 % of grid points within 100 km of a given grid point have $f \geq 0.8$. The results for a single grid point, containing the Lambourn catchment, are shown in Figure 5.2. As would be expected, the proportion of grid points with higher *f* values drops off quite rapidly with distance from the reference grid point in the Lambourn catchment, whereas lower *f* values persist at greater distances. For higher *f* values, the decay is less rapid during the wet season than during the dry season, but for lower *f* values there is not much difference between the seasons.

There were marked contrasts between the profiles of SCD_{70} and SCD_{90}, particularly at high *f* thresholds (*e.g.*, $f \geq 0.8$, 0.9). For SCD_{70}, the proportion of grid points with high *f* values within shorter distances was significantly larger than those for SCD_{90}.

5.4 Results

5.4.1 Drought covariance index

Figure 5.3 shows the covariance index (*CI*) at all DSI time scales for the dry and wet seasons under moderate and extreme drought conditions. *CI* is generally higher during the wet season and for moderate and shorter duration droughts, and lower during the dry season and for extreme and longer duration droughts. Almost all of the UK has a $CI_{70} \geq 0.7$ for DSI3 and DSI6 during the wet season, whereas during the dry season large parts of the UK have $CI_{70} < 0.7$. When extreme droughts are considered, *CI* is less than 0.6 for DSI3 over much of the UK during the wet season and drops below 0.5 over large areas during the dry season.

Spatially, CI_{70} during the wet season is highest in the north and west of the UK, especially for shorter durations. CI_{70} during the dry season is similar across much of the UK, except for longer duration droughts in which the *CI* is higher in

England and lower in Scotland and Wales. For extreme droughts, CI tends to be higher in England, especially for longer duration events.

Table 5.2 summarizes the percentage of the UK represented by different CI intervals for all DSI time scales for the dry and wet seasons under the two drought severities. It shows that most of the UK is represented by at least 0.4 and 0.6 for CI_{90} and CI_{70}, respectively. There is a mean difference of 15 % between each DSI time scale in terms of percentage area, with greater difference between DSI3 and DSI15. For both drought severities, the wet season shows a higher proportion of the domain represented by any given coherence threshold.

5.4.2 Spatial coherence decay

Following the previous section, the percentage area represented by CI ≥0.8 within 100 km, 200 km, 300 km and 400 km from each reference grid cell at DSI6 and DSI15 is mapped. Spatial coherence decay (SCD) for moderate and extreme droughts are show in Figure 5.4 (dry season) and Figure 5.5 (wet season). For DSI6, the dry season shows $SCD_{70}^{0.8}$ ≥0.2 within 100 km, indicating that at least 20 % of the area within 100 km of respective grids are represented by CI ≥0.8 under moderate drought conditions. There is a gradual decline in the percentage area for other distances considered in which the reduction is larger for most of Scotland, Wales and southwest England. The pattern at DSI15 under the same drought intensity indicates a significantly larger area with $SCD_{70}^{0.8}$ <0.25 for each distance considered. This encompasses nearly all of Scotland, Northern Ireland and Wales. As with DSI6, most of England did not show any major reduction.

The patterns for DSI6 and DSI15 are similar under extreme drought conditions, although DSI6 shows considerably more grids with $SCD_{90}^{0.8}$ ≥0.2 for all distances. In both cases, most of the grids in the domain (apart from southeast England) have less than 10 % of the area within the given distance represented by CI ≥0.8. Within southeast England, there is a significant decrease in both the percentage area and the total grid points that have more than 15 % of the area represented by CI ≥0.8 for each given distance.

For the wet season (Figure 5.5), almost all grids show $SCD_{70}^{0.8}$ ≥0.5 within 100 km and 200 km at DSI6. Within 300 km and 400 km, most of England and Northern Ireland show $SCD_{70}^{0.8}$ ≥0.5 for the same drought length and season. At DSI15, most of England has $SCD_{70}^{0.8}$ ≥0.5 for all distances, while the rest of the domain show $SCD_{70}^{0.8}$ between 0.25 and 0.4.

There is almost no difference in patterns of $SCD_{90}^{0.8}$ at DSI6 and DSI15, although the latter shows slightly more grid points with $SCD_{90}^{0.8}$ ≥0.1. Most grids in southeast England are characterized by $SCD_{90}^{0.8}$ between 0.15 and 0.3 within 100 km of respective grids. For greater distances, there is a reduction in the proportion of grid points in southeast England with $SCD_{90}^{0.8}$ between 0.15 and 0.3.

5.5 Discussion

Patterns of spatial coherence of two drought severities for the UK for different drought durations and seasons are investigated. In this section, three important outcomes of this study, which relate to the observed differences in seasonal, temporal and intra-regional coherence, are discussed. In addition, the implications of this study for drought management are examined.

The results of this study display an inverse relationship between the magnitude of coherence and DSI time scale (*i.e.*, the length of drought). This can be explained by the rarity of drought events at longer DSI, which in turn reduces their detectability and decreases the probability of common drought years between grid cells.

The seasonal difference in coherence, which shows greater coherence magnitude and spatial extent during the wet season, suggests that wet season droughts are more a function of larger scale circulation anomalies, such as the North Atlantic Oscillation (NAO). The relationship between NAO and UK precipitation has been studied by, for example, Wilby *et al*. (1997), who showed positive correlation between winter NAO and regional rainfall amounts in northern and southern Scotland and northwest England, whereas negative correlations were recorded in southern, central and northeast England. These findings were shared by Fowler and Kilsby (2002b), who confirmed this pattern for sites in northern England. In the UK, droughts occur during the negative phase of winter NAO, which is associated with below-average precipitation (López-Moreno and Vicente-Serrano, 2008). This, in part, explains the greater occurrence and coherence of droughts during the wet season in this study.

The observed intra-regional differences can be partly explained by spatial variability of precipitation within regions. In the study of Yorkshire droughts, Fowler and Kilsby (2002a) noted that the behaviour of droughts in the region can be divided into two groups – a Pennine group and an east of the Pennines group. This classification of droughts corresponds well with the division of Yorkshire, which has two climatologically distinct regions. In an earlier study, Phillips and McGregor (1998) showed that droughts in southwest England (Devon and Cornwall) are more coherent both in terms of timing and severity for the north coast locations of their study area. This spatial variability coincides with a large precipitation deficit between the north and south. The results of this study on intra-regional differences in coherence are therefore consistent with the observations from these previous studies.

In the context of drought management, the option of water transfer – a method in which water is supplied to a drought region from areas not experiencing drought – is of limited applicability in the case of (1) moderate, (2) short duration and (3) wet season droughts in which coherence is not only higher, but also covers a spatially larger area. This in turn suggests that most of the UK experiences the same drought event(s). Conversely, the prospect for water transfer arises in the case of (1) extreme, (2) dry season and (3) long-duration droughts that are most coherent within England.

Droughts occurring during the wet season have shown to be spatially more coherent. Regions whose water resource systems are dependent on recharge during the wet season, more critically England, are likely to show more sensitivity, hence greater vulnerability to droughts. Nonetheless, a region's vulnerability to drought does not only depend on the contribution from groundwater, river flow and other water storage systems like reservoirs, which serve to moderate the severity of a drought event, but also how such resources are managed. The 2003 UK drought is an example of how integrated management of water resources resulted in a modest impact of drought in the country as a whole (Marsh, 2004). This contrasts with the 1995 drought, which had high stress because of poor management of water resources (Marsh, 1996; Walker and Smithers, 1998). In the UK, drought orders and drought permits are commonly used strategies adopted by water companies to restrict non-essential usage of water or allow them to extract water from sources other than those specified in their abstraction licence (Environment Agency, 2011). One of the other options under drought condition is water transfer.

This study gives the opportunity to understand and assess the scope of drought coherence in the UK from 1914 to 2006, an aspect that is rarely considered in water resources planning in the UK. Results identify areas that have a propensity for coherent meteorological drought-stress (*e.g.*, southeast England) and those areas that do not tend to co-vary in terms of drought (generally northern locations). Based on the idea of spatial coherence, water transfer operates on the basis that water is supplied from areas that have different coherence characteristics than the receiving location. This ensures that water is supplied from areas that are not likely to experience drought at the same time as the receiving location. If drought is experienced at any given location, it is likely that water can be transferred from areas farther away from the catchment, *i.e.*, regional transfer. Those closer to the drought location are more likely to experience the same drought, as can be inferred from the Lambourn catchment (Figure 5.1). The scope of water transfer for an average situation (Figure 5.3) would involve an inter-regional or even long-range transfer. However, adopting water transfer as a drought response measure is a complex issue with inherent cost and environmental implications (Environment Agency, 2006). In addition, it is also important to note that the main factor making a location a suitable source for water transfers is long-run surplus, and not necessarily drought that are uncorrelated with the recipient location. Finally, this study provides a baseline against which to assess drought coherence in regional climate models and a baseline against which to assess projected changes in the coherence of extreme droughts.

5.6 Conclusion

Historical records have shown that drought is a recurring feature of the UK's climate (Marsh *et al*., 2007). Experiences of past events have shown varying responses to droughts, some of which have been well managed, whereas lessons could be learned from others. Responses to future droughts would have to consider both demand management and supply augmentation. For supply augmentation, a key concern is how water can be supplied to an area without jeopardising the sustainability of the area supplying the water and where the potential areas of supply could be. In part, this study addresses the latter by presenting a climatology of droughts in terms of their extent and magnitude over a 93-year historical period. The authors believe the results are useful in understanding the spatial behaviour of droughts and identifying drought-stress, as well as drought-free, areas so that better management decisions relating to supply augmentation and demand management can be implemented in response to future drought events.

Table 5.1: Summary of literature on historical drought in the UK with an emphasis on scope of study, methodology and main observations.

Author (Year)	Scope of study	Methodology	Main observations
Bryant *et al.* (1994)	Analysis of 1988-92 drought in the context of long duration droughts (1850-1992) in England.	Deficit index applied to monthly observed and synthetic river flow data from nine catchments.	Extreme drought is evident in eastern and southern England. Droughts in the 150 year record do not last more than four years.
Marsh *et al.* (1994)	Documents the development of the 1988-1992drought.	Not applicable	The 1988-1992 drought is attributed to the combination of unusual weather systems and abnormally high temperatures.
Marsh (1996)	Documents the development of the 1995 drought.	Not applicable	The 1995 drought is attributed to weather patterns and the unprecedented demand for water.
Jones and Lister (1998)	Development of reconstructed river flow dataset and assessment of hydrological droughts since 1865.	6 and 18 month deficit index applied to reconstructed river flow data at 15 catchments.	Catchments in northern and western England and Wales experience more short duration droughts compared to those in the south and east of England which are groundwater-fed.
Phillips and McGregor (1998)	Formulation of a drought index to assess drought hazard from 1950-1996 in southwest England.	Utility of the drought severity index on a 6 month time scale to monthly precipitation at four sites.	Observed spatial variability in the timing and extent of coherence between stations which could be explained by weather types and/or frontal systems.
Walker and Smithers (1998)	Review of 1995-1996 drought in northwest England in the context of water resource management.	Not applicable	Low rainfall during summer 1995 accompanied by unusually high temperatures led to the unprecedented high demand of water for domestic use.

Fowler and Kilsby (2002a)	Studying the relationship between weather types and droughts from 1881-1998 in Yorkshire, England.	Application of drought severity index at 3 and 6 month time scales to monthly precipitation data at five sites.	High spatial variability of droughts in the Yorkshire region is observed. Droughts are classified based on the nature of the weather-types that persist.
Marsh (2004)	Documents the development of the 2003 drought event and a review of its resilience.	Not applicable	Integrated management of water resources provided greater scope for responding to supply shortfalls.
Marsh (2007)	Documents the development of the 2004-2006 drought in southern Britain with particular reference to the impact on water resources.	Not applicable	Change in weather-types shows how quickly a drought event can turn into an event that poses risk of flooding.
Marsh *et al.* (2007)	Assessment of drought characteristics since 1800 with particular attention to regional vulnerability.	Not applicable	Increase in 20th century summer droughts is driven by rising temperatures. Winter rainfall is of primary importance especially when groundwater is the principal supply source.

Table 5.2: Percentage of domain represented by a given coherence threshold for the dry and wet seasons at DSI3, DSI6, DSI12 and DSI15. Results are shown for drought covariance index (*CI*) for extreme and moderate droughts (90th and 70th percentile exceedance, respectively).

	Dry season				Wet season			
	DSI3	DSI6	DSI12	DSI15	DSI3	DSI6	DSI12	DSI15
(a) Extreme droughts								
$CI \geq 0.0$	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
$CI \geq 0.1$	100.0	100.0	99.4	99.1	100.0	100.0	99.8	99.8
$CI \geq 0.2$	99.8	98.3	93.2	93.2	100.0	100.0	96.2	94.8
$CI \geq 0.3$	96.3	88.7	76.6	77.4	99.7	96.3	88.4	89.0
$CI \geq 0.4$	83.8	64.6	32.8	28.5	95.2	86.0	61.7	53.9
$CI \geq 0.5$	27.0	8.0	0.5	0.5	69.5	40.5	15.9	8.6
$CI \geq 0.6$	0.5	0.0	0.0	0.0	7.3	1.6	0.3	0.0
$CI \geq 0.7$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$CI \geq 0.8$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$CI \geq 0.9$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(b) Moderate droughts								
$CI \geq 0.0$	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
$CI \geq 0.1$	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
$CI \geq 0.2$	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
$CI \geq 0.3$	100.0	100.0	100.0	99.8	100.0	100.0	100.0	100.0
$CI \geq 0.4$	100.0	99.7	98.9	98.1	100.0	100.0	99.2	99.1
$CI \geq 0.5$	100.0	98.9	92.1	92.7	100.0	99.8	98.3	97.5
$CI \geq 0.6$	99.1	90.3	62.2	70.9	99.8	99.2	91.1	88.1
$CI \geq 0.7$	57.1	26.9	6.8	7.5	99.4	91.9	46.1	35.6
$CI \geq 0.8$	0.3	0.0	5.9	1.9	65.5	20.2	12.7	26.7
$CI \geq 0.9$	0.0	0.0	5.9	1.9	12.7	6.2	12.7	26.7

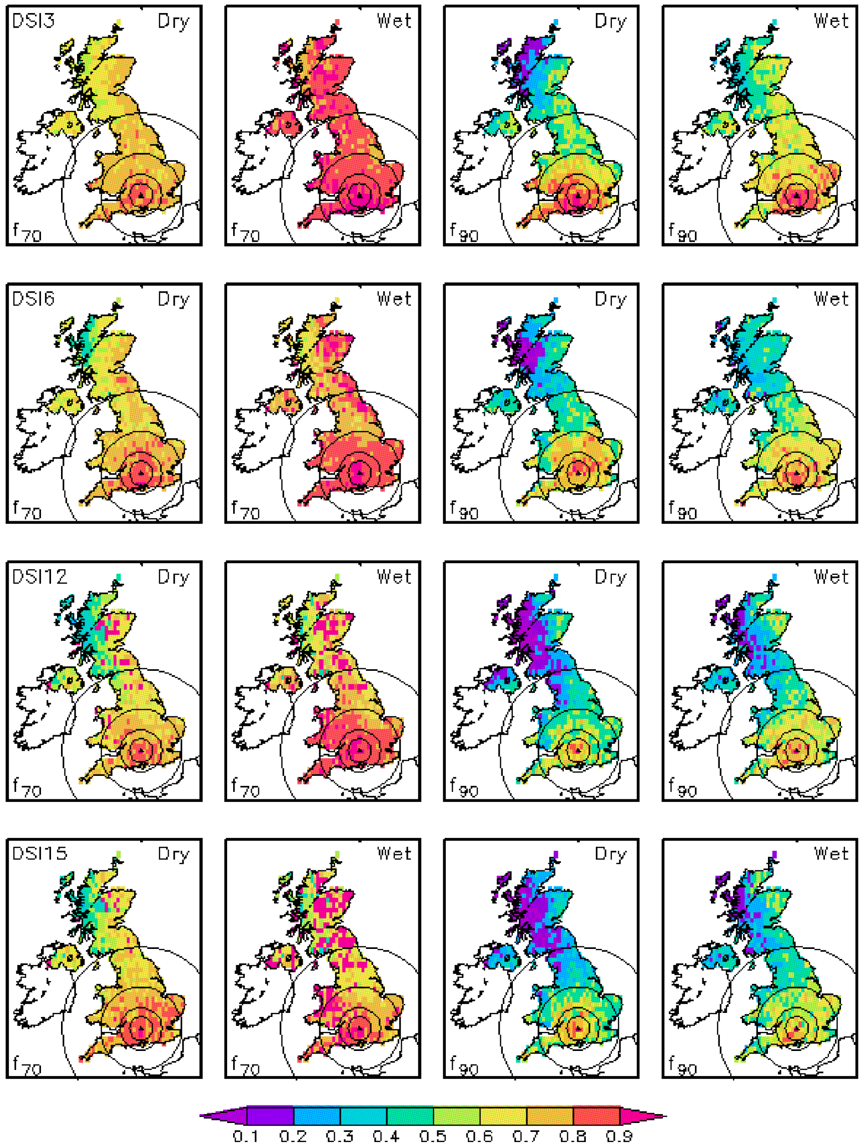

Figure 5.1: Fraction of common years (f) for the Lambourn catchment at various DSI time scales for the wet and dry seasons for moderate and extreme droughts (f_{70} and f_{90}, respectively. Location of catchment is marked with black triangle. Circular lines show 50 km, 100 km, 200km and 400 km distances from the centre. Colour bar represents the fraction of common years.

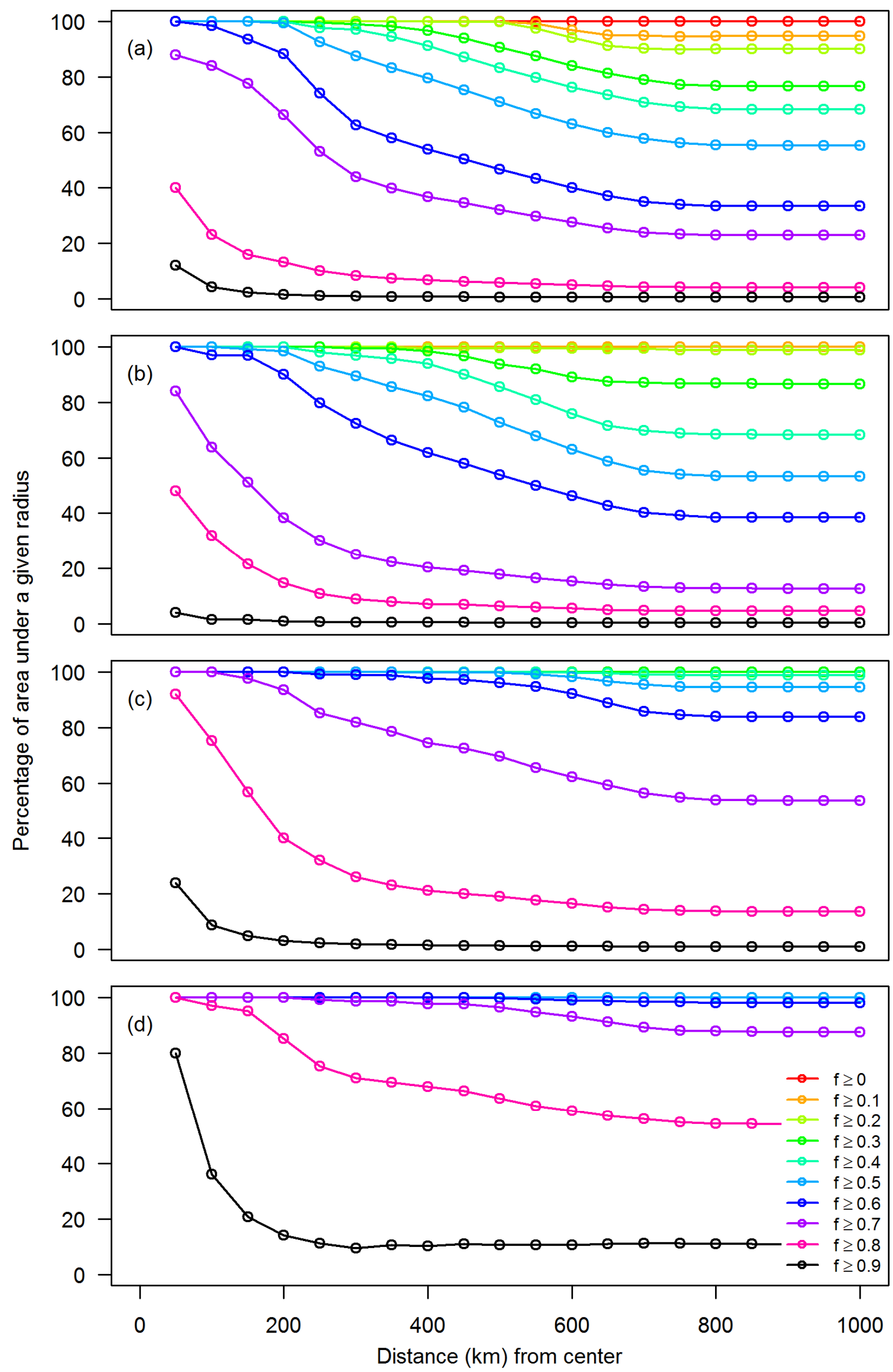

Figure 5.2: Profiles of spatial coherence decay for the Lambourn catchment at various *f* thresholds at DSI6 for moderate and extreme droughts (70th and 90th percentile exceedance, respectively) and for the dry and wet seasons. (a) Extreme drought, dry season, (b) extreme drought, wet season, (c) moderate drought, dry season and (d) moderate drought, wet season.

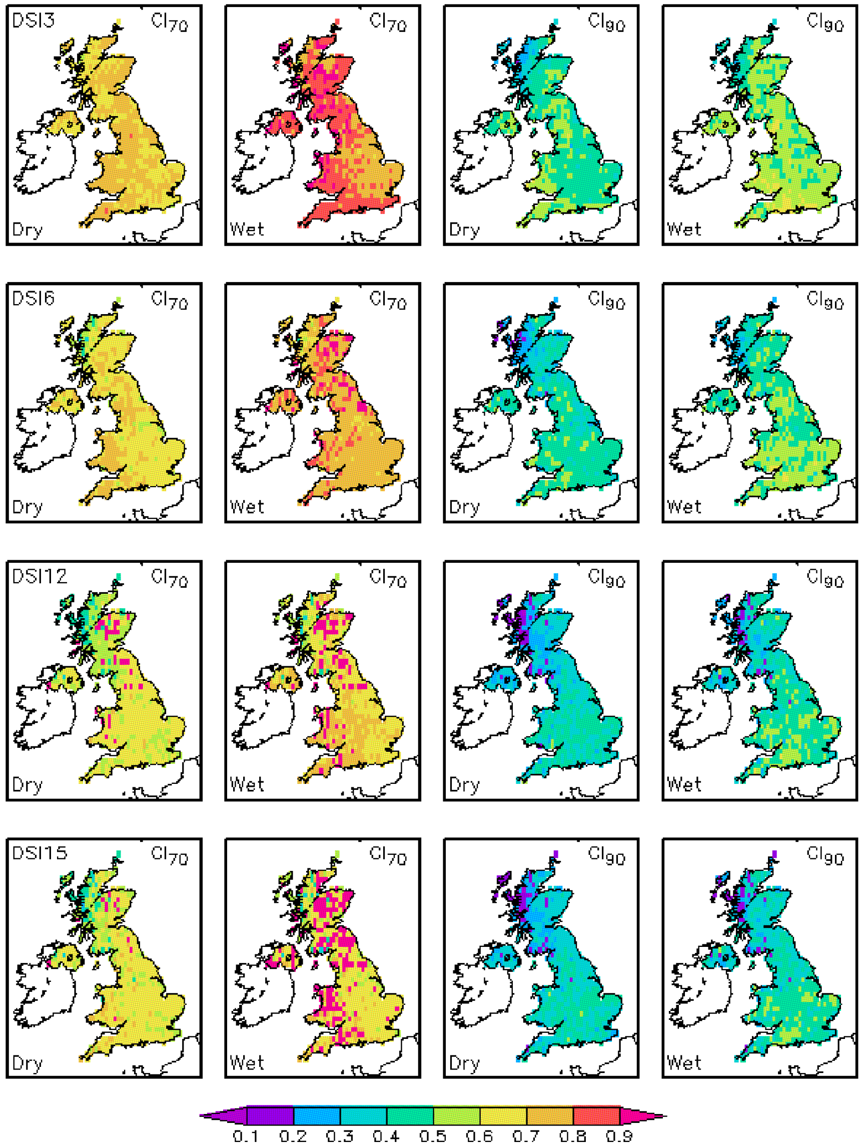

Figure 5.3: Drought covariance index at various DSI time scales for the dry and wet seasons for moderate and extreme droughts (annotated CI_{70} and CI_{90}, respectively). Colour bar represents the degree of pairwise covariance.

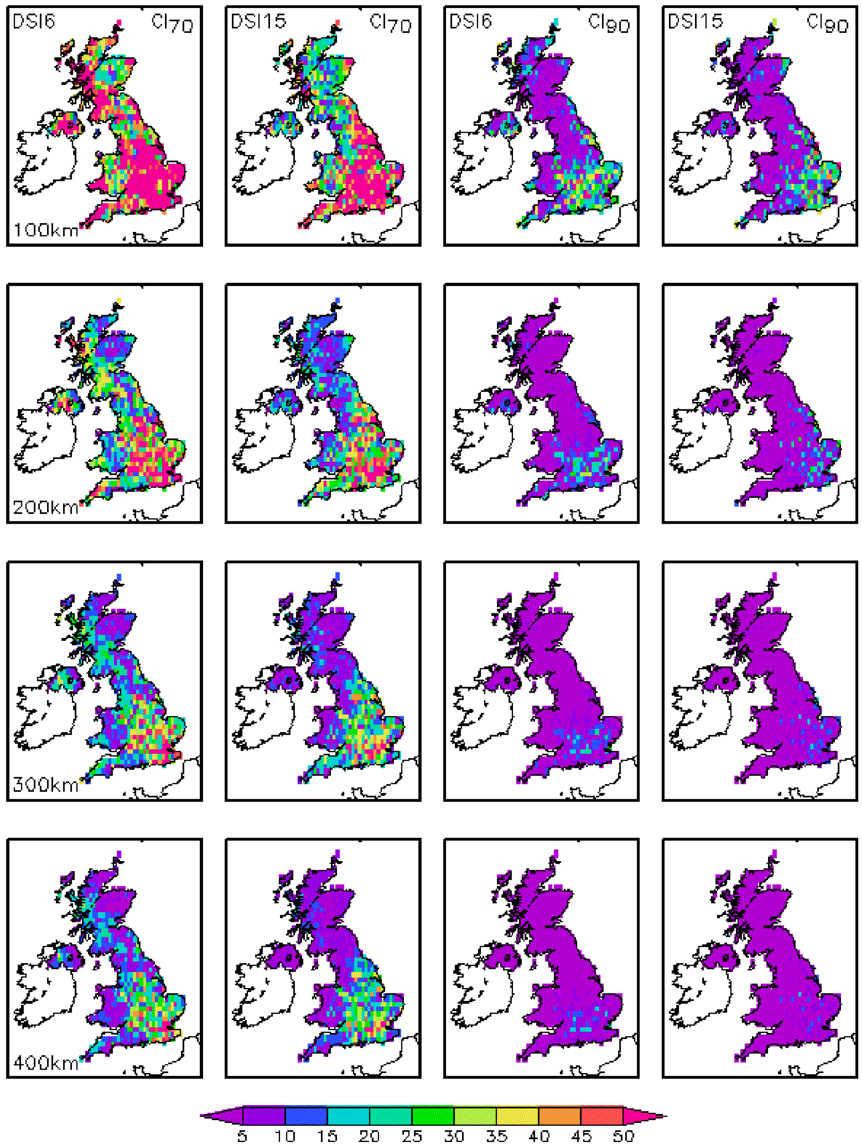

Figure 5.4: Percentage area represented by CI ≥0.8 within 100 km, 200 km, 300 km and 400 km from each reference grid at DSI6 and DSI15 for moderate and extreme droughts (annotated CI_{70} and CI_{90}, respectively) during the dry season. Colour bar expresses the percentage area represented by CI ≥0.8 within the specified distance of each grid.

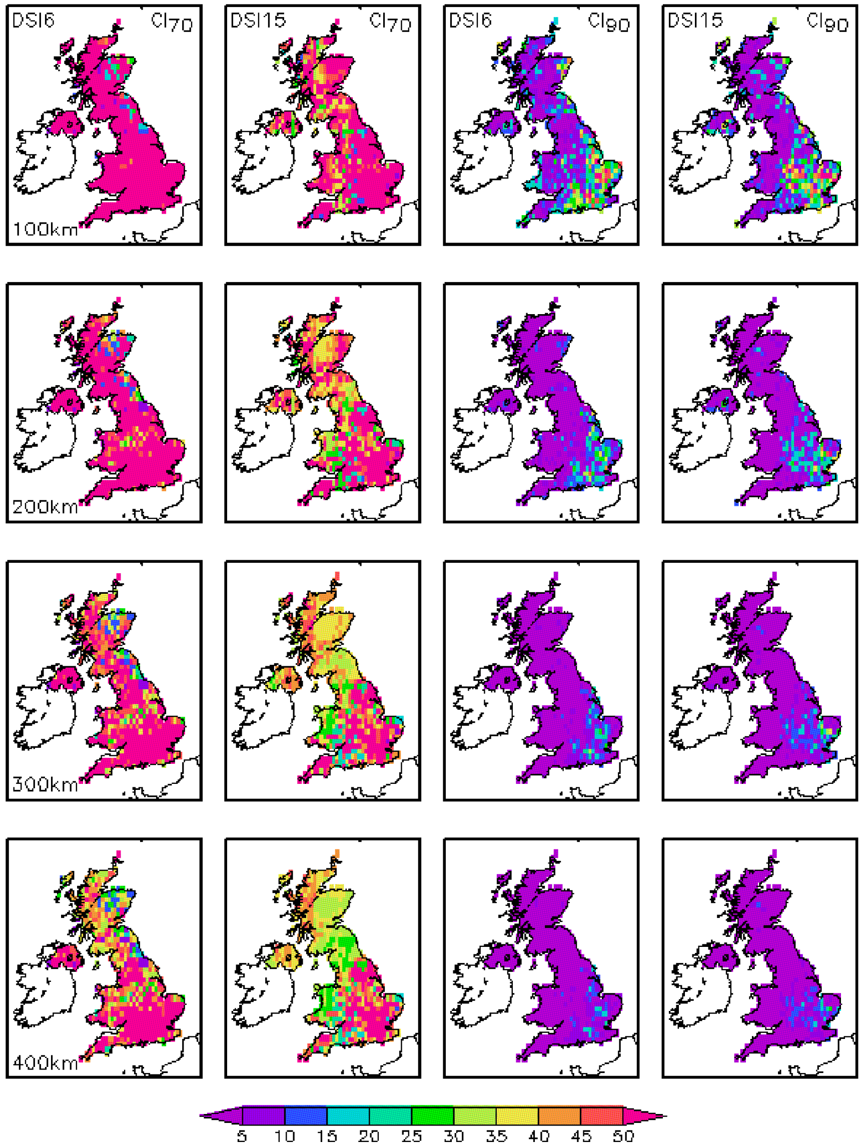

Figure 5.5: As Figure 5.4, but for the wet season.

Chapter 6

Evaluation of HadRM3-PPE-UK: Drought Characteristics

Abstract

This chapter addresses the third research objective of the thesis: "*To assess the reliability of the UKMO perturbed physics RCMs, used in the recent UKCP09, in their representation of drought characteristics*". The chapter is currently under review with *Journal of Climate*.

The rationale of this chapter is to assess the reliability of the HadRM3-PPE-UK in simulating present-day droughts, and to explore differences in reliability across the ensemble members. The HadRM3-PPE-UK was developed for the UK Climate Projections 2009 (UKCP09) to provide climate change information for assessments of climate change risks and adaptation responses in the UK. Understanding the uncertainties in the simulation of present-day droughts provides a gauge on the confidence associated with using the dataset for projections of 21st century droughts in the UK to facilitate such assessments.

A 6-month drought severity index (DSI6) is applied to monthly precipitation from the 11-member HadRM3-PPE-UK regional climate model (RCM) dataset to evaluate the ability of its members to simulate four observed drought characteristics, namely drought intensity (*DI*), drought covariance index (*CI*), frequency of drought months (*FDM*), and frequency of drought events at a given

duration (*FDD*), under different drought severity (moderate and extreme) and seasonal (dry/summer and wet/winter) conditions. The HadRM3-PPE-UK is also evaluated in terms of the members' ability to reproduce the mean seasonal rainfall (*msRAIN*) and mean seasonal DSI6 (*msDSI6*), and their leading principle components. In addition, cross correlation analyses, across all the 23 water resource regions (WRRs), between the 11-member RCMs, and between the biases in both dry and wet season indices are performed to assess the inter-model and inter-index consistency in reproducing the spatial patterns of bias. Results of the study are summarized as follows:

- Mean seasonal rainfall (*msRAIN*): Negative ensemble mean bias across the UK during the dry season whereas the wet season shows positive biases over England and Wales but negative biases over Scotland and Northern Ireland. Ensemble spread is larger during the dry season than the wet season;

- Mean seasonal DSI6 (*msDSI6*): Negative ensemble mean bias across most regions during the dry season. In contrast, positive ensemble mean bias is shown over most of the UK during the wet season. Both seasons show large ensemble spread, larger during the wet season;

- Principal component (PC) analysis: Excellent consistency in the space-time covariance between the 11-member RCMs and the observed data for *msRAIN* during both dry and wet seasons. *msDSI6* lacks the spatial consistency between the models and the observed data, but shows better agreement across models;

- Bias in drought intensity (*DI*): The dry season is characterized by negative ensemble mean bias covering all regions under both drought severities. This contrasts with the wet season which shows positive bias across the UK, with lower ensemble mean bias for extreme droughts. Ensemble spread is largest during the wet season under moderate drought conditions, whereas comparable magnitude ensemble spread is shown for all other conditions;

- Bias in drought covariance index (*CI*): All conditions show small and positive ensemble mean bias except during the wet season under moderate drought conditions which shows negative biases, covering largely Wales and Northern Ireland. Positive bias is larger during the dry season under extreme drought conditions. Ensemble spread is considerably large in all situations, although smaller ensemble spread is shown during the wet season under moderate drought conditions;

- Bias in frequency of drought months (*FDM*): Negative and positive ensemble mean biases shown during the dry and wet seasons, respectively. The magnitudes of bias between the two drought severities are comparable. For all conditions, the ensemble spread is large;

- Bias in frequency of drought events at a given duration (*FDD*): Ensemble mean bias shows largely positive biases (<4 events) for FDD_3 and FDD_6 under both moderate and extreme drought conditions, whereas longer persistence durations (*i.e.*, FDD_{10} and FDD_{12}) are characterized by negative biases (within 1.8 events). The ensemble spread is relatively large for short persistence durations and generally decreases with increasing persistence duration;

- Cross correlation analyses show good consistency, as shown by the positive correlations, between the models in reproducing the spatial patterns of bias for any given drought index across all WRRs. Consistency in the spatial patterns of bias across all WRRs is also shown between the biases in wet season indices, but not between the biases in the dry season indices or between the biases in dry and wet season indices;

- High and statistically significant positive correlation is shown between the biases in *DI* and *msDSI6*. There is also better consistency in the sign, magnitude and spatial patterns of biases between *msDSI6* and the drought characteristics. Results therefore suggest that the biases in the seasonal drought indices are underpinned by the *msDSI6*, rather than the bias in *msRAIN*; and

- No relationship between a model's climate sensitivity and the sign, magnitude and/or spatial patterns of bias in a given index can be inferred. This suggests that sensitivity of the RCM does not influence the magnitude of bias in *msRAIN*, *msDSI6* or other drought indices.

The significance of results from this study is that it shows the importance of evaluating climate models in terms of drought characteristics, compared with that in terms of rainfall statistics which do no present a complete picture of the uncertainties of in the model to assess its reliability to simulate present-day and future droughts.

6.1 Introduction

Global and regional climate models (GCMs and RCMs, respectively) have been used as tools to project future climates. However, the results of the projections are still confronted with varying degrees of confidence, which can be lower for certain geographical locations, seasons and variables. The varying degrees of confidence is due to the inherent uncertainties attributed to modeling future climates, namely the incomplete understanding and/or ability to model earth-system processes, natural climatic variability and future emissions (Hawkins and Sutton, 2009).

In terms of extreme events such as droughts and floods, the Intergovernmental Panel on Climate Change (IPCC) states that there is medium confidence that such events will intensify in the 21st century, referring to 5 out of 10 chance that such events will happen in the future. The IPCC reasons that "*confidence in projecting changes in the direction and magnitude of climate extremes* *depends on many factors, including the type of extreme, the region and season, the amount and quality of observational data, the level of understanding of the underlying processes, and the reliability of their simulation in models*." (IPCC, 2012).

The aim of this paper is to present an evaluation of the 11-member regional climate model from the perturbed physics ensemble experiment over the UK (HadRM3-PPE-UK) in terms of drought statistics. The rationale of the study is as follows:

- Droughts, a recurring feature of the UK's climate, have been identified in the UK Climate Change Risk Assessment (CCRA) as a potential impact arising from future climate change that transcends economic, social and environmental sectors;

- There is a need to gauge the confidence associated with using the HadRM3-PPE-UK for projections of 21st century droughts in the UK (*see* Burke *et al*., 2010; Burke and Brown, 2010; Rahiz and New, 2012). The HadRM3-PPE-UK was developed for the UK Climate Projections 2009 (UKCP09) to provide climate change information for assessment of risks and adaptations in the UK. It differs from multi-model ensemble experiments (MME) in that it allows uncertainties within the model to be quantified, in contrast with MME which looks at uncertainties between models. This would provide better understanding of the physical basis of climate change, in addition to providing opportunities for assessing the impacts of climate change under a range of possible outcomes;

- Evaluation of the HadRM3-PPE-UK therefore serves as a guidance to understand the reliability of the dataset in simulating droughts, thus facilitating efforts to identify risks, reduce vulnerabilities and increase resilience;

- Evaluation of the HadRM3-PPE-UK also allows some of the factors that account for any bias in the dataset to be explored, hence shedding some light on the mechanisms driving the uncertainties in models which in turn would be useful for future model development; and

- Evaluation in terms of drought statistics is presented because the application of a drought index, as frequently used in drought studies, may involve some form of data transformation resulting in an index which may have a new statistical characteristics compared with the original data from which the index was derived.

The paper uses the following organization: Chapter 6.2 provides background of commonly used methods in climate model evaluation. Chapter 6.3 details the methodology, providing information on model and reference datasets, drought index, seasonal and severity classifications, drought characteristics and other analyses. Results from the analyses for each of the ensemble members, including regionally-averaged bias over the 23 water resource regions (WRRs) in the UK, are given in Chapter 6.4. A discussion of results focusing on the possible basis of the uncertainties and a conclusion is provided in Chapter 6.5.

6.2 Evaluation methods

There is no universally agreed method in which a climate model can be evaluated (Räisänen, 2006; Dessai and Hulme, 2008; Schaller *et al*., 2011). While it may be convenient to have a standard objective method against which models can be assessed, the lack of it allows models to be scrutinized from a variety of perspectives (Randall *et al*., 2007; Johns *et al*., 2010). The most widely used approach of assessment is through quantifying the model's bias, which is defined as the difference between (usually) 30-year averaged value of a historical simulation and the corresponding observed averaged value (Giorgi and Francisco, 2000). Other performance measures, such as root mean square error (Bozkurt *et al*., 2010; Dadson *et al*., 2011), mean and standard deviation (Giorgi and Francisco, 2000) have also been frequently used.

Depending on the objective of the study, other characteristics of model-observed differences may be investigated. For example, Dai (2006) evaluated precipitation characteristics, such as mean spatial patterns, seasonal variability, frequency and intensity, in 18 GCMs against several observed datasets; Sylla *et al*. (2012) focused on hydroclimatic indices, such number of wet days and mean maximum wet/dry spell length, to assess the ability of the RegCM RCM to simulate the spatial characteristics of daily rainfall over East, South and West Africa, using

ERA-Interim (Dee *et al*., 2011) gridded reanalysis dataset as the reference data. The authors also investigated the onset, peak and withdrawal of monsoon season for their study area.

The availability of climate datasets from various climate modeling centres through international cooperation such as the Coupled Models Intercomparison Program Phase 3 and 5 (CMIP3/5) for GCMs or the European PRUDENCE (http://prudence.dmi.dk) and ENSEMBLES (http://ensembles-eu.metoffice.com) projects and more recently the CORDEX program (http://wcrp-cordex.ipsl.jussieu.fr) for RCMs allows for the assessment of the "spread" of results across models. The ensemble spread, calculated as the difference in the maximum and minimum values across the ensemble, is often used as an indicator of uncertainties in climate simulations (Solman and Pessacg, 2012). Such work is seen in the study by, for example, Buser *et al*. (2010) on present-day (1961-1990) precipitation simulations from four RCMs from the PRUDENCE project and Schaller *et al*. (2011) using 24 GCMs from the CMIP3 project.

In the context of UK drought studies, climate models have largely been evaluated in terms of the bias between modeled and observed precipitation statistics over recent climatological reference periods (Blenkinsop and Fowler, 2007b; Fowler and Kilsby, 2007; Burke *et al*., 2010). Evaluation of climate models in terms of their ability to reproduce present-day UK drought characteristics includes:

- Fowler and Kilsby (2004) applied a 3- and 6-month drought severity index

(DSI; Philips and McGregor, 1998) to both the gridded observed and RCM (HadRM3H) data to assess model bias in terms of the duration and severity of droughts;

- Vidal and Wade (2009) evaluated the ability of six GCMs to reproduce the observed frequency and magnitude of extreme droughts using the standardized precipitation index (SPI; McKee *et al*., 1993) on 3-, 6-, 12- and 24-month time scales;

- Burke and Brown (2010) compared the HadRM3-PPE-UK with the observed data in terms of several drought characteristics (*i.e.*, area, severity, frequency, return period and probability) using a 12-month drought metric; and

- In the study by Maule *et al*. (2013), the time series of regional SPI (RSPI) and the self-calibrated Palmer drought severity index (sc-PDSI), both modified versions of the SPI and the PDSI (Palmer, 1965), respectively, for 23 European regions (including four from the UK) from 14 ENSEMBLES RCMs were compared against that of the observed data to which the RSPI and sc-PDSI have also been applied (van der Schrier *et al*., 2006; Parry *et al*., 2011).

6.3 Methodology

6.3.1 Data

Two datasets, covering the entire UK domain, are used: 1) monthly precipitation from 11-member HadRM3-PPE-UK (Murphy *et al*., 2007) of the Met Office Hadley Centre's regional climate model, HadRM3, developed for the 2009 UK Climate Projections (UKCP09); and 2) monthly gridded observed rainfall (Perry and Hollis, 2005). The HadRM3-PPE-UK spans the period 1950-2099 and uses a rotated pole grid with a 25 km spatial resolution (Jones *et al*., 2004). Individual ensemble members have climate sensitivities between 2.5 K and 7.1 K (Table 6.1). The monthly gridded rainfall spans from 1914-2006 and has a spatial resolution of 5 x 5 km. To maintain spatial and temporal consistencies for ease of comparison, both datasets have been regridded to a longitudinal/latitudinal grid of 0.225° (approximately the HadRM3 resolution) and the common period 1950-2006 is used.

6.3.2 Drought severity index

A rainfall-based drought index, the drought severity index (DSI) is used to characterize droughts. The DSI is based on an *n* month cumulative precipitation anomaly (Bryant *et al*., 1994) and termination rule (Mawdsley *et al*., 1994). The anomaly is defined relative to a given reference period, which in this study is with respect to the mean monthly precipitation from 1961-1990. A 6-month DSI (DSI6) is used in this study as a six-month cumulative precipitation anomaly is often thought to be representative of hydrological droughts. The DSI6's algorithm is described as follows (after Phillips and McGregor, 1998);

Consider the rainfall anomaly in month *t,* denoted X_t. If X_t is negative (*i.e.* below its mean level) and rainfall in the six month period, X_t, X_{t-1}, X_{t-2}, …, X_{t-5} is lower than its six monthly mean, then initiate a drought sequence in month *t,* assigning the DSI a positive value that is equal to the precipitation deficit in month *t.*

Now consider the month $t+1$. Suppose the rainfall anomalies in months t and $t+1$ were $-X$ mm and $-Y$ mm, respectively, then the DSI6 for month $t+1$ equals $X + Y$, if and only if the six monthly mean total for the months t-4, t-3, t-2, t-1, t and $t+1$ has not been exceeded. If the rainfall anomaly is positive in month $t+1$, then a drought can continue, with DSI6 = $X - Y$, provided that the six monthly mean total has not been exceeded. All drought sequences are terminated immediately when this six monthly mean total has been exceeded and DSI6 is assigned a value of zero.

To allow for comparison between locations, the index is standardized by dividing the DSI6 values by the location's mean annual rainfall and then multiplying by 100. The final index value will thus express the accumulated precipitation deficit as percentage of the mean annual rainfall of the location.

6.3.3 Seasonal disaggregation

The DSI6 time series are then separated into dry and wet seasons covering the months of April-September and October-March, respectively, following Rahiz and New (2012). (Note: subscripts d and w are used to denote the dry and wet seasons, respectively, throughout the paper). The disaggregation is based on the UK hydrological year and therefore reflects the hydrological variability in terms of winter storage and summer drawdown. This is more meaningful in the context of water resources management and planning as opposed to the conventional climatologically-defined seasonal classes (December-January-February, and so on) or calendar seasons. As an illustration, the seasonally disaggregated DSI6 for the dry period would contain the six DSI6 values for April to September of each year from 1950-2006.

6.3.4 Principal component (PC) analysis

A principal component (PC) analysis is a form of multivariate data reduction technique that aims to describe the underlying patterns of the data by extracting the components which account for the greatest proportion of total variance. A PC analysis is performed on both the mean seasonal rainfall and mean seasonal DSI6 (*msRAIN* and *msDSI6*, respectively) for each of the 11 ensemble members and the observed dataset to establish if there is consistency in capturing the broad-scale precipitation and drought inter-annual covariance across the datasets during the dry and wet seasons.

6.3.5 Drought characteristics

The skill of the HadRM3-PPE-UK is evaluated in terms of its ability to simulate drought characteristics, using the same characteristics as have been applied in a separate study (Rahiz and New, 2013): drought intensity (*DI*), drought covariance index (*CI*), frequency of drought months (*FDM*), and frequency of drought events at a given duration (*FDD*). These characteristics are analyzed under extreme and moderate drought conditions defined as events which exceed the 90th and 70th percentiles of the given DSI6 time series, respectively. The calculation of each characteristic is given below (after Rahiz and New, 2013) and computed on a grid point-by-grid point basis for each ensemble member and the observed dataset.

- Drought intensity (*DI*): Defined as the 90th and 70th percentile thresholds of the entire seasonal DSI6 time series;

- Drought covariance index (*CI*): Quantifies the spatial coherence of drought events. It is calculated by first identifying the years with moderate (or extreme) droughts, as defined above. Next the fraction of years, *f*, with moderate (or extreme) droughts that each pair of grid points has in common is determined. Finally, for each grid point, the covariance index (*CI*) is calculated as the average of all pairwise *f* values for that grid point. This provides the average state of drought covariance of any given grid point with relative to all others;

- Frequency of drought months (*FDM*): The *FDM* for a given season is defined as the number of drought months in the period 1950-2006 that exceeds the 90th (or 70th) percentile of the entire annual DSI6 time series; and

- Frequency of events at a given duration (*FDD*): *FDD* is defined as the sum of the frequency of drought events exceeding the 90th (or 70th) percentile of the annual DSI6 time series for the period 1950-2006, with persistence of at least 3, 6, 10 and 12 months (FDD_3, FDD_6, FDD_{10} and FDD_{12}, respectively). [Note: no seasonal subsetting is done on *FDD*].

6.3.6 Water resource regions (WRRs)

For each ensemble member, the bias in drought characteristic calculated relative to the observed data is regionally-averaged over 23 water resource regions (WRRs) in the UK (Figure 6.1). The WRRs are used by the Environment Agency (England and Wales), the Scottish Environment Protection Agency and Northern Ireland Environment Agency for strategic planning and reporting to the European Commission for the Water Framework Directive (EU Directive 2000/60/EC). The use of WRRs in this study therefore provides a useful gauge of the uncertainties in the simulation of present-day droughts for each region, which in turn would inform the reliability of projection of future droughts over these regions.

6.3.7 Cross correlation analyses

Two cross correlation analyses using Spearman's rank correlation, with statistically significant correlation defined at the 90 % confidence level, are performed: 1) cross correlation, across all WRRs, between the biases in the drought indices during the dry and wet seasons and under both drought severities for each ensemble member, and 2) cross correlation, across all WRRs, between the 11-member ensemble for the biases in each drought index and for each season and drought severity condition. The two cross correlation analyses provide an assessment of the spatial consistencies in reproducing the patterns of bias between the indices and between the RCMs, respectively. Thus, positive correlations between the biases in any two indices (or the bias in any given index between any two RCMs) indicate agreement in the sign of the bias between the indices (or RCMs). Likewise, negative correlations between the biases in any two indices (or the bias in any given index between any two RCMs) indicate the lack of agreement in the sign of the bias between the indices (or RCMs).

6.4 Results

Due to the large number of characteristics evaluated, illustrations are shown only for extreme droughts during the dry season which, generally portray the strongest drought signal. Figures and tables for the wet season and also for moderate droughts are provided in Appendices A and B. Summary data for all seasons, drought characteristics and drought intensities are provided in accompanying tables.

6.4.1 Bias in mean seasonal rainfall (*msRAIN*)

Figure 6.2 shows the bias in $msRAIN_d$. Three of the models – afixc, afixj and afixk – have strong negative biases, whereas two other models – afgcx and afixh – have strong positive biases. The remaining members generally show weak (±15 %)

positive and negative biases, generally covering the northeast and southwest sections of the UK, respectively. The bias in $msRAIN_{\mathrm{w}}$ shows a more consistent spatial pattern across the 11-member ensemble, with strong wet bias over Anglian and Thames, and strong dry bias over Argyll, west and north highlands (Figure A-1 in Appendix B). No relationship can be inferred between the sensitivity of the model and the bias in *msRAIN*. This presents new information on the role of model sensitivity in the generation of rainfall biases in the HadRM3-PPE-UK which, to the authors' knowledge, have not been investigated in other studies which employed the same dataset (*e.g.*, Burke *et al.*, 2010; Burke and Brown, 2010; Murphy *et al.*, 2010).

Table 6.2 provides a summary of regionally-averaged bias in *msRAIN* over the 23 WRRs in terms of the ensemble mean, maximum, minimum bias and its spread, and the number of models showing agreement in the sign of bias. For each WRR the ensemble spread is large, greater during the dry season (domain average = 40 %) than the wet season (domain average = 16 %). The ensemble mean bias shows encouraging results with most of the WRRs registering biases within ±10 % during both seasons.

6.4.2 Bias in mean seasonal DSI6 (*msDSI6*)

The bias in $msDSI6_{\mathrm{d}}$ (Figure 6.3) is largely negative across all ensemble members and the ensemble mean, with greatest bias shown over various regions in England, more commonly over northern England. The proportion of domain characterized by positive bias is small and of lower magnitude (within 20 %). The case for *msDSI6*$_{w}$ (Figure A-2 in Appendix B) shows significant contrast compared with *msDSI6*$_{d}$ with most of the models showing large positive biases, particularly over Wales and England. For two ensemble members, afgcx and afixh, most of England is shown with negative biases within 20 %.

For both seasons, the ensemble spread is large, with higher magnitude during the wet season (Table 6.3). Both seasons also show large ensemble mean bias, averaging -23 % and 33 % during the wet and dry seasons, respectively.

6.4.3 Principal component (PC) analysis

The loadings of the first ten PCs for *msRAIN* and *msDSI6* are given in Table 6.4 (dry season) and Table 6.5 (wet season). For *msRAIN*, the loadings of PC 1 between the dry and wet seasons are similar, accounting for 83-93 % (Table 6.4a) and 91-95 % (Table 6.5a) of the variance, respectively. There is excellent consistency in the spatial patterns of PC 1 between each member of the ensemble and the observed dataset with both seasons showing an east-west contrast, with greatest variance over England and west Highland (Figure 6.4 – dry season and Figure A-3 in Appendix B – wet season).

For *msDSI6*, PC 1 explains 16-29 % and 23-34 % of the variability during the dry (Table 6.4b) and wet (Table 6.5b) seasons, respectively. There is a lack of consistency in the spatial patterns of PC 1 between each ensemble member and the observed dataset (Figure 6.5). Although greatest variance is also shown over England and west Highland, there is considerable regional variability over England across the datasets. The case for the wet season on the other hand shows better spatial consistency between the datasets (Figure A-4 in Appendix B). Most models show greatest variance shown over southwest/southeast England and Anglian. For the observed dataset, the magnitude of variance over these regions is significantly lower.

Unlike *msRAIN*, a large proportion of variance in *msDSI6* can also be explained by PCs 2, 3 and 4 which account for an average of 7-11 % of the variability during the dry season (7-13 % during the wet season). The spatial patterns of the PCs show either a lack of or no consistency between the model and observed data, but better agreement across the ensemble members (Figure A-5 to Figure A-10 in Appendix B).

6.4.4 Bias in drought intensity (*DI*)

The bias in DI_d for extreme droughts (Figure 6.6) shows underestimation largely over England (highest over Humber, Thames and Anglian regions) and overestimation generally over Scotland and parts of northern England. The case for DI_d under moderate drought conditions shows widespread underestimation in *DI*, largest over different regions in England (Figure A-11 in Appendix B).

There is generally overestimation in DI_w under extreme drought conditions (Figure A-12 in Appendix B), although this varies across models with a few showing large positive bias over parts of England, whereas small biases (±15 %), or even large negative bias, are shown in others. For moderate droughts (Figure A-13 in Appendix B), there is large overestimation covering the almost entire domain.

Statistics for regionally-averaged bias in DI (Table 6.6) shows large ensemble spread (domain average = ~50 %) across seasons and drought intensities, largest for DI_w under moderate drought conditions (domain average = 132 %). DI_w under moderate drought conditions also shows higher ensemble mean bias (domain average = 87 %), compared with other conditions which show significantly lower bias (domain average = -22 % to 11 %)

6.4.5 Bias in drought covariance index (*CI*)

Most of the models show positive biases in CI_d under extreme drought conditions, greatest over most of England, Wales and Northern Ireland (Figure 6.7). The magnitude of bias is lower for moderate droughts with most models showing, on average, positive biases of 20 % over most of England and Wales, and with remaining areas showing biases within ±10 % (Figure A-14 in Appendix B).

The case for CI_w under extreme drought conditions shows largely positive biases over Northern Ireland, Wales, northern and southwest England, whereas negative biases are shown over the Scottish Highlands, northeast Scotland and southeast England (Figure A-15 in Appendix B). The pattern contrasts with moderate droughts (Figure A-16 in Appendix B) which show a significantly lower magnitude of bias (±10 %) with most of the ensemble members showing negative biases over east and southeast England.

Table 6.7 details the regionally-averaged bias for each of the 23 WRRs. The table shows relatively large ensemble mean spread (domain average between 12

% and 72 %) across all seasons and severity levels, and greater for extreme droughts. When the ensemble mean is considered, low bias (domain average = ±10 %) is registered for all other conditions, except for CI_d under extreme droughts (domain average = 23 %).

6.4.6 Bias in frequency of drought months (*FDM*)

The bias in FDM_d for extreme droughts (Figure 6.8) is largely characterized by negative bias, with highest underestimation (>40 %) shown over most regions in England and small overestimation (10-20 %) over northeast Scotland and lowland regions. Similar spatial pattern is shown for moderate droughts (Figure A-17 in Appendix B), but with higher magnitude of negative bias characterizing a larger area.

The biases in FDM_w under extreme and moderate drought conditions (Figure A-18 and Figure A-19 in Appendix B, respectively) show contrasting pictures: positive biases characterize most of the domain with greatest bias magnitude (>40 %) over large areas in England, and with moderate droughts showing generally greater (and more widespread) bias.

All seasons and drought severities show consistently large ensemble spread, with domain average between 32 % and 52 % (Table 6.8). The ensemble mean is also consistently large (±30 %), with negative biases shown for FDM_d.

6.4.7 Bias in frequency of drought events at a given duration (*FDD*)

The bias in *FDD* for extreme droughts with persistence of at least 3 months (FDD_3)

(Figure 6.9) shows small bias of ±2 events, with most of the models generally showing positive biases over England and negative biases over northeast Scotland, northwest England and Northumbria. As the duration of persistence increases (*i.e.*, FDD_6, FDD_{10} and FDD_{12}), the models show progression towards negative biases (and lower magnitude) covering large parts of the domain (Figure A-20 to Figure A-22 in Appendix B).

The pattern of bias for FDD_3 for moderate droughts (Figure 6.10) is similar to that for extreme droughts, but with greater bias magnitude. There is high positive bias (>8 events) which characterizes large parts of the domain, whereas greatest negative bias (>8 events) is shown largely over Scotland and northern England. Most of England and Wales show largely positive bias, although the magnitude of bias varies across models. The case for FDD_6 (Figure A-23 in Appendix B) shows lower magnitude of positive bias compared with FDD_3, whereas FDD_{10} and FDD_{12} (Figure A-24 and Figure A-25 in Appendix B, respectively) show are characterized by largely negative biases over most regions in England and Wales.

The bias between the model and the observed data does not necessarily reflect the deficiency of the model in reproducing the observed drought characteristic. It could also be due to the low (or no) detectability of events especially under extreme drought conditions and for longer persistence durations by the model and/or observed data.

Table 6.9 and Table 6.10 summarize the regionally-averaged bias for the 23 WRRs for moderate and extreme droughts, respectively. The magnitude of bias for the ensemble spread is small *i.e.*, between 1.7 to 3.6 events (moderate droughts), and between 3.9 to 10.4 events (extreme droughts). There is more consistency in the ensemble mean bias across both drought severities (domain average = ±1.4 events). Both ensemble spread and ensemble mean show decreasing magnitudes of bias with increasing persistence durations.

6.4.8 Cross correlation analyses

The cross correlation, across all WRRs, between the bias in the indices for all seasons under extreme drought conditions for each ensemble member is given in Table 6.11 (results for moderate droughts – Table A-3 in Appendix A – are largely consistent with extreme droughts hence will not be discussed). Each ensemble member largely shows the following: 1) negative correlations between biases in dry and wet season indices. This can be explained by the fact that the dry and wet season indices are largely associated with negative and positive biases, respectively, across the WRRs; 2) positive correlations between the biases in wet season indices. Positive correlations between the biases in the indices are expected considering that the indices are largely inter-dependent, with strong dependency on the behaviour of *msRAIN* and/or *msDSI6*. Therefore, a positive bias in *msDSI6*, for example, would bring about positive biases in other indices, such as *DI* and *FDM*; and 3) marginally more negative (but low magnitude) correlations between the biases in dry season indices.

High and statistically significant positive correlation is shown between the biases in *DI* and *msDSI6* during the dry and wet seasons for all models. This suggests that the biases in *DI* are underpinned by the biases in *msDSI6* rather than the biases in *msRAIN* which showed contrasting results during the dry and wet seasons (*i.e.*, largely negative and positive correlations, respectively).

Positive correlations are largely seen between the biases in *msDSI6* and *FDM* are seen during the dry and wet seasons. The relationship is expected as the biases in *FDM* are generated by the biases in *DI*, which in turn is generated by the biases in *msDSI6*. However, the correlation between the biases in *msDSI6* and *CI* is largely negative. This is because the bias in *CI* is positive whereas other indices show negative biases. Unlike other indices, the calculation of *CI* is not directly dependent on *msDSI6*, rather the fraction of common years at a given drought intensity between any two grid points. During the dry and wet seasons, the models show higher frequencies of common years at a given drought intensity, hence higher *CI*, compared with the observed data.

Cross correlation, across all WRRs, between the 11-member ensemble for the biases in each drought index shows statistically significant positive correlations (Table A-4 to Table A-10 in Appendix A). The magnitudes of correlation are generally similar across seasons and drought severities, indicating that the sensitivity of the models has little effect on the biases in the indices. The results of this cross correlation analysis therefore show good consistency between the models in reproducing the spatial bias of any given index.

6.5 Discussion and conclusions

The 11-member HadRM3-PPE-UK is evaluated against the UK gridded observed precipitation dataset to assess its ability to simulate four observed drought characteristics, namely drought intensity (*DI*), drought covariance index (*CI*), frequency of drought months (*FDM*), and frequency of drought events at a given duration (*FDD*) under different severity and seasonal conditions. The models are also assessed in terms of their ability to reproduce basic characteristics such as mean seasonal rainfall (*msRAIN*) and mean seasonal DSI6 (*msDSI6*), and their covariance. Key results from the analyses are summarized as follows (*cf.* Table 6.12):

- Bias in mean seasonal rainfall (*msRAIN*): Ensemble mean shows negative bias (within 9 %) across the domain for $msRAIN_d$, whereas $msRAIN_w$ shows positive biases over England (7 %) and Wales (3 %) but negative biases over Scotland (-7 %) and Northern Ireland (-8 %) (Table 6.12a). Ensemble spread is larger for the $msRAIN_d$ than for $msRAIN_w$;

- Bias in mean seasonal DSI6 (*msDSI6*): Ensemble mean shows negative (within 40 %) and positive (>30 %) biases across most regions for $msDSI6_d$ and $msDSI6_w$, respectively (Table 6.12b). Both seasons show large ensemble spread, which is larger for $msDSI6_w$;

- Principal component (PC) analysis: For *msRAIN*, there is excellent consistency in the space-time covariance between the models and the observed data during both seasons. Spatial consistency is lacking between the models and the observed data for *msDSI6*, but better agreement across models;

- Bias in drought intensity (*DI*): Ensemble mean shows negative biases (within 27 %) for all regions for the DI_d under both moderate and extreme droughts (Table 6.12c). The DI_w on the other hand shows positive biases across the domain, with lower ensemble mean bias for extreme droughts (between 6 % and 17 %) compared with moderate droughts (>49 %). The ensemble spread is largest for DI_w under moderate drought conditions, whereas for all other conditions the ensemble spread is comparable;

- Bias in drought covariance index (*CI*): Except for Wales and Northern Ireland which show negative ensemble mean biases (within 2 %) for CI_w under moderate drought conditions, all other conditions are characterized by small positive biases (<14 %) (Table 6.12d). However, larger positive bias is shown CI_d under extreme drought conditions (between 8 % and 25 %). Ensemble spread is considerably large in all cases, although smaller ensemble spread is shown for CI_w under moderate drought conditions;

- Bias in frequency of drought months (*FDM*): Negative ensemble mean bias (within 27 %) is shown for FDM_d, whereas positive bias (between 8 % and

34 %) is shown for FDM_w (Table 6.12e). The magnitudes of bias between the two drought severities are comparable. For all conditions, the ensemble spread is large;

- Bias in frequency of drought events at a given duration (*FDD*): Ensemble mean bias shows largely positive biases (<4 events) for FDD_3 and FDD_6 under both moderate and extreme drought conditions, whereas longer persistence durations (*i.e.*, FDD_{10} and FDD_{12}) are characterized by negative biases (within 1.8 events) (Table 6.12f and Table 6.12g). The ensemble spread is relatively large for short persistence durations and generally decreases with increasing persistence duration; and

- Cross correlation analyses: Cross correlation analyses show the consistency between the models, and between the indices, in reproducing spatial patterns of bias across the WRRs. Positive correlations are largely shown between the RCMs for the bias in any given drought index, and between the biases in wet season indices for any given model.

The findings in this study are largely consistent with the evaluation of the HadRM3-PPE-UK by Burke *et al*. (2010) who reported a northwest-southeast (drier-wetter) contrast in the bias in the 12-month cumulative precipitation. However, results of the ensemble mean bias in the present study show variations across indices, seasons and drought severities, with Scotland (and to a certain extent, Northern Ireland) characterized by negative, lower negative, or lower positive biases compared with England and Wales (Table 6.12).

Burke *et al*. (2010) suggested that the bias in the HadRM3-PPE-UK, especially over northwest Scotland, can partly be attributed to the unresolved topography in the model based on their findings of a smaller standard deviation (in terms of mean monthly precipitation) across the ensemble members than the reference data. Their study also concluded that the biases in the ensemble member are due to the downscaling of the regional model, and not differences in boundary conditions. The bias over Scotland shown in this study may be explained by unresolved topography as suggested by the Burke *et al*. (2010). To an extent, the strong bias signal over east and southeast England as shown in several models may also be explained by poor representation of convection in the model. This reasoning is drawn from the study by Fowler *et al*. (2005) who evaluated the HadRM3H against observed datasets (focusing on extreme precipitation) in which they attributed the underestimation of precipitation over the southeast and southwest of the UK to poor convection in the RCM. The bias in the HadRM3 can also be explained by the inability of the models to reproduce large scale atmospheric circulations (Murphy et al., 2009). Analysis of the North Atlantic storm track using the perturbed-physics HadCM3 ensemble showed that the individual models followed a southerly (and weaker strength) track during winter (and likewise for other seasons) than the observed position as derived by the ECMWF ERA40 re-analysis of observations. Similarly, the HadCM3 ensemble was generally not able to reproduce observed anticyclonic blocking events for both the winter and summer seasons, although some aspects of the blocking have been reasonably simulated over the North Atlantic region during winter.

There is no relationship between the sensitivity of the ensemble members and the magnitude, sign and/or statistical significance of the correlation. Nonetheless, consistently strong and statistically significant positive correlation is shown between the biases in *msDSI6* and *DI* during both seasons across all models. Similar consistency is also largely shown for *msRAIN* but with either lower (wet season) or negative (dry season) correlation. This also suggests that the biases in the drought indices are, to a large extent, influenced by the biases in *msDSI6.*

This paper presents a study that investigates the uncertainties in the 11-member HadRM3-PPE-UK in terms of their ability to simulate observed drought characteristics. The individual ensemble members are not able to reproduce the observed drought characteristics, exhibiting either large underestimation or overestimation in any given drought characteristic, or even stronger bias magnitude over a given region compared with the rest of the UK. However, there is better consistency in the spatial distribution of the bias which generally shows a northwest-southeast contrast across the ensemble members.

There is agreement in the sign of bias across the indices, and ensemble members. The ensemble spread is generally large, indicating the high level of uncertainty in the dataset. The finding agrees with that of Burke *et al*. (2010) who reported a ±30 % bias across the 11-member HadRM3-PPE-UK. This is expected given the nature of the perturbed-physics ensemble experiment which results in different realizations of climate, hence different drought patterns. When the ensemble mean is used, there is a closer resemblance of observed drought characteristics (*i.e.*, lower magnitude of bias). However, the use of ensemble mean to inform model uncertainties needs to be treated with care because the biases in the models cancel each other, giving an optimistic impression of the model performance (Räisänen, 2007; Schaller *et al*., 2011).

Much of the physical basis driving the uncertainties in the HadRM3-PPE-UK remains to be understood. Studies have attributed the uncertainties in the models to the downscaling of the RCM and poor representation of convection in the models (Fowler *et al*., 2005; Burke *et al*., 2010). This study shows that the biases in the drought characteristics are largely influenced by the biases in *msDSI6*, and to a lesser extent, *msRAIN*.

Evaluation of the models in terms of *msRAIN* produces spatial patterns of bias (and/or bias magnitudes) that contrast with that in terms of drought characteristics (*DI*, *CI*, *FDM*, and *FDD*), but when *msDSI6* is considered, there is better consistency in the spatial patterns, magnitude and sign of bias (Table 6.12). The biases in *msRAIN* and *msDSI6* are largely opposite, indicating that the original data had undergone some form of transformation that changes its statistical characteristics when the drought index is applied to it. This analysis therefore shows that the evaluation of models solely in terms of rainfall characteristics do not provide a complete picture of the uncertainties to inform the reliability of a dataset in simulating present-day and future droughts.

In conclusion, this paper provides some information on the uncertainties in the application of HadRM3-PPE-UK in the context of droughts in the UK. It is hoped that results are able to guide users to the authors' research on 21st century drought scenarios in the UK (Rahiz and New, 2013) using the HadRM3-PPE-UK dataset.

Figure 6.1: The 23 water resource regions (WRRs) used in this study. Map source: Jenkins *et al.* (2009)

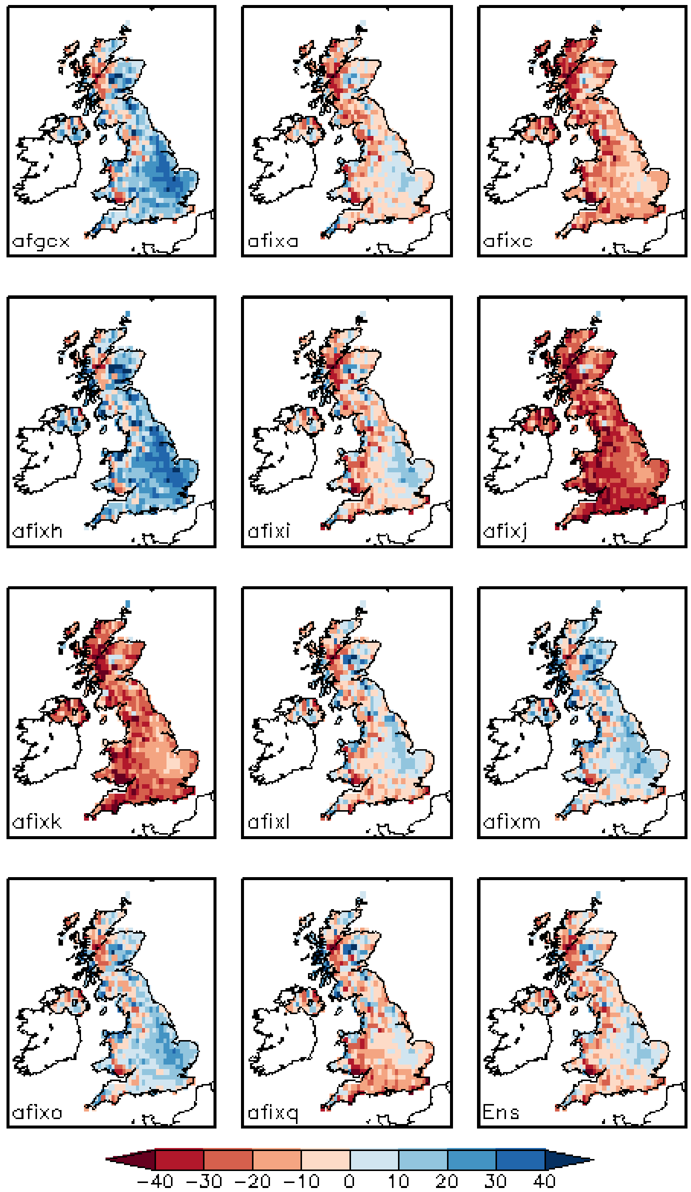

Figure 6.2: Bias in mean seasonal rainfall (*msRAIN*) during the dry season for each of the 11-member ensemble (afgcx to afixq). Color bar shows the percentage change relative to the observed data. Ens refers to the ensemble mean bias.

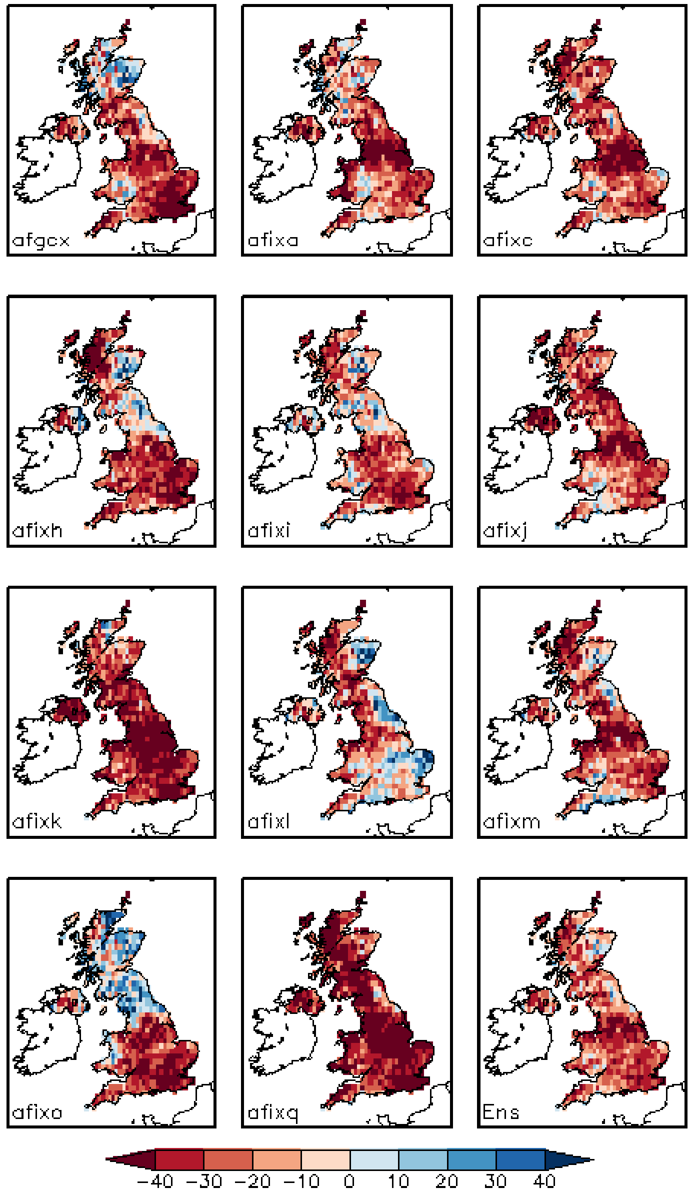

Figure 6.3: As Figure 6.2, but for mean seasonal DSI6 (*msDSI6*).

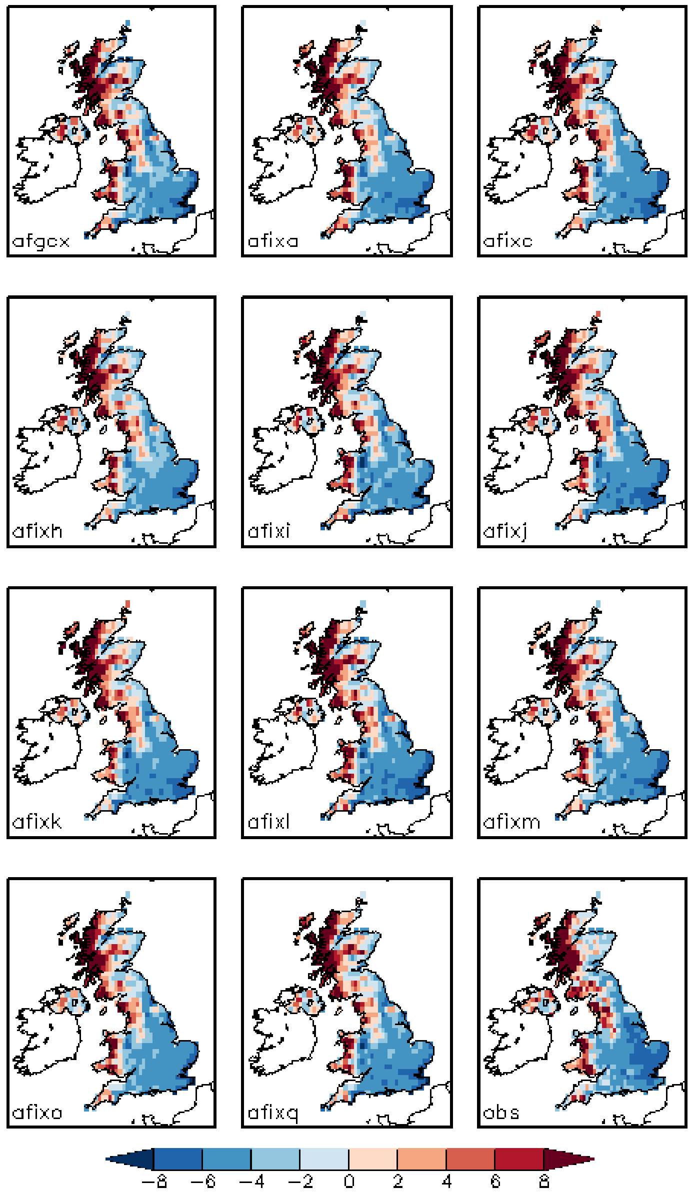

Figure 6.4: Spatial patterns of the first principal component (PC 1) for mean seasonal rainfall (*msRAIN*) during the dry season for each of the 11-member ensemble (afgcx to afixq) and the observed (obs) data.

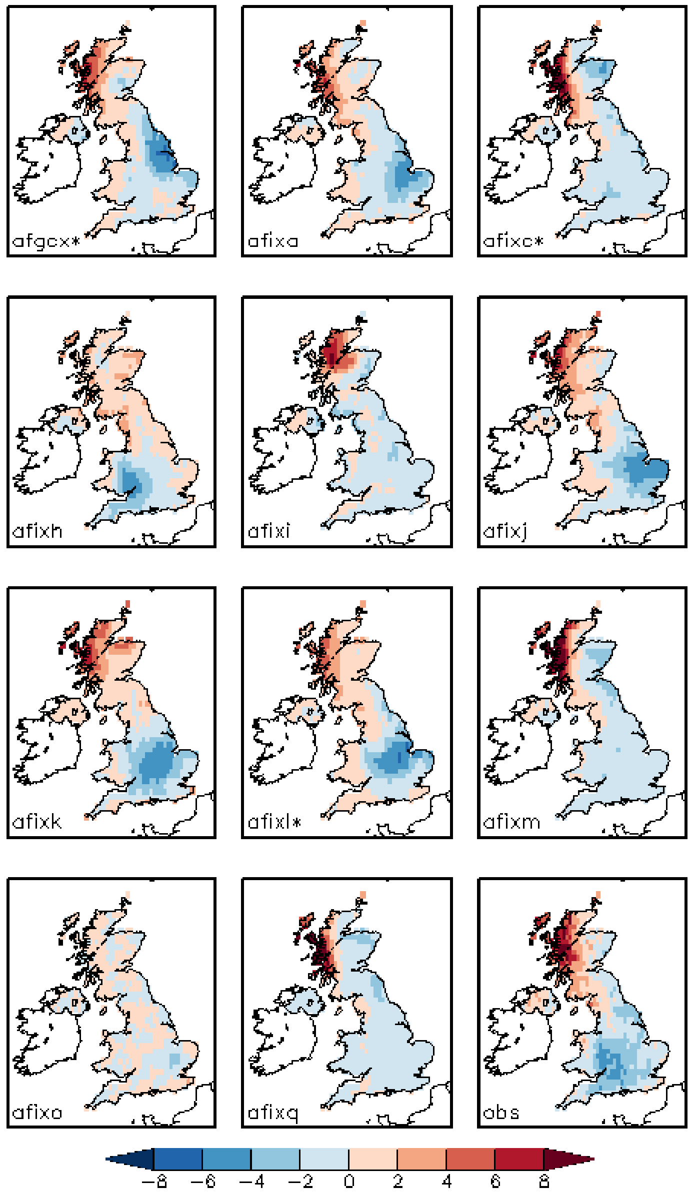

Figure 6.5: As Figure 6.4, but for mean seasonal DSI6 (*msDSI6*).

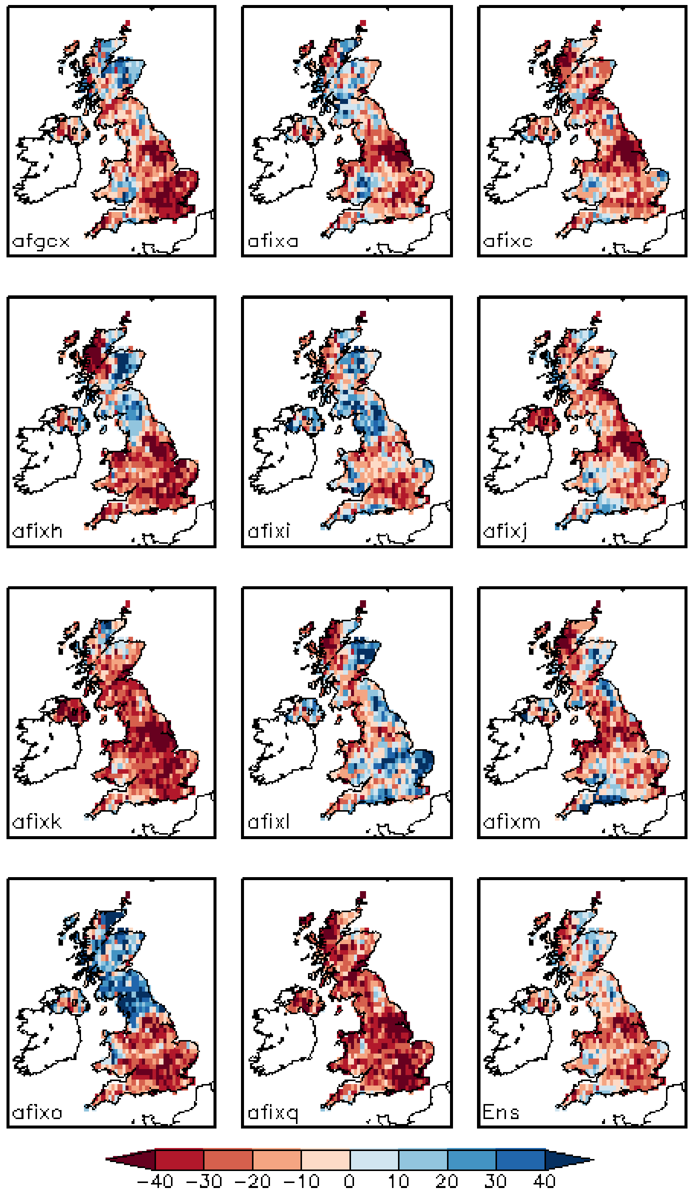

Figure 6.6: Bias in drought intensity (*DI*) during the dry season under extreme drought conditions for each of the 11-member ensemble (afgcx to afixq). Color bar shows the percentage change relative to the observed data. Ens refers to the ensemble mean bias.

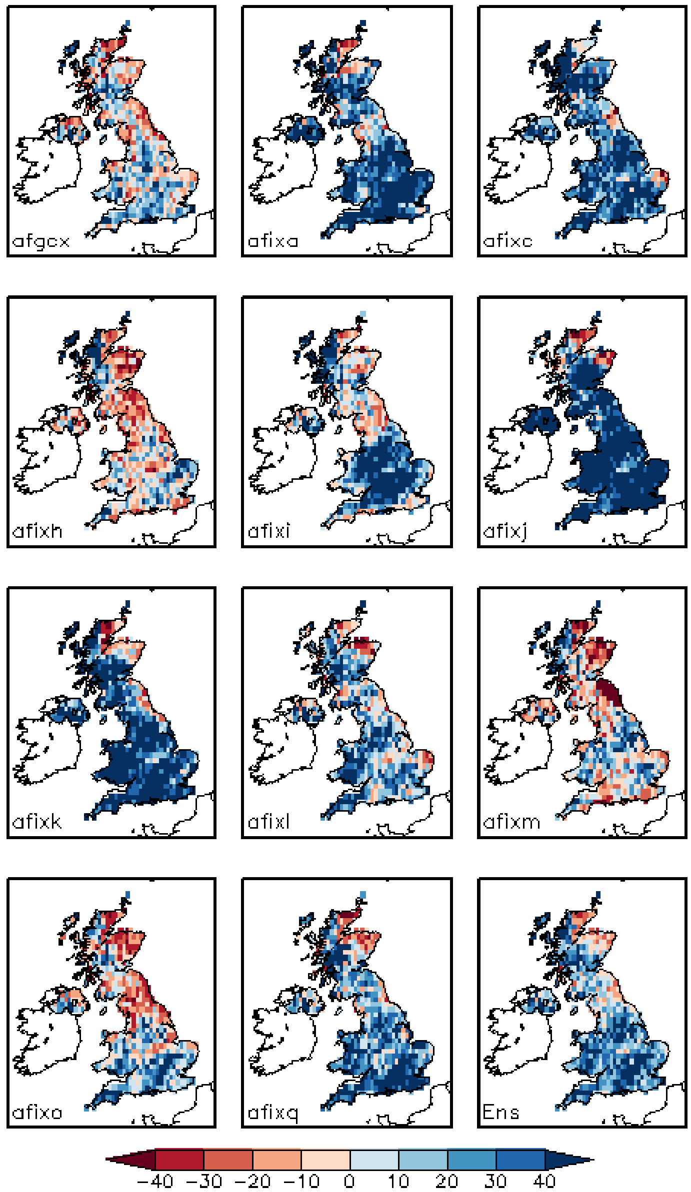

Figure 6.7: Bias in drought covariance index (*CI*) during the dry season under extreme drought conditions for each of the 11-member ensemble (afgcx to afixq). Color bar shows the percentage change relative to the observed data. Ens refers to the ensemble mean bias.

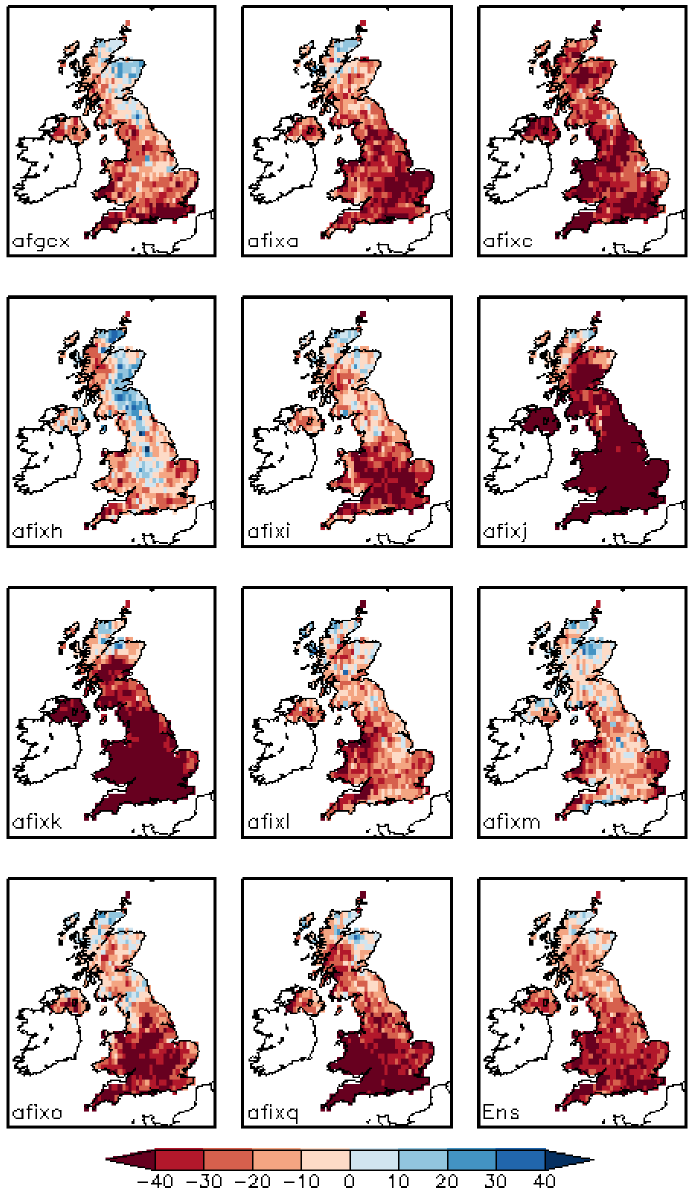

Figure 6.8: Bias in frequency of drought months (*FDM*) during the dry season under extreme drought conditions for each of the 11-member ensemble (afgcx to afixq). Color bar shows the percentage change relative to the observed data. Ens refers to the ensemble mean bias.

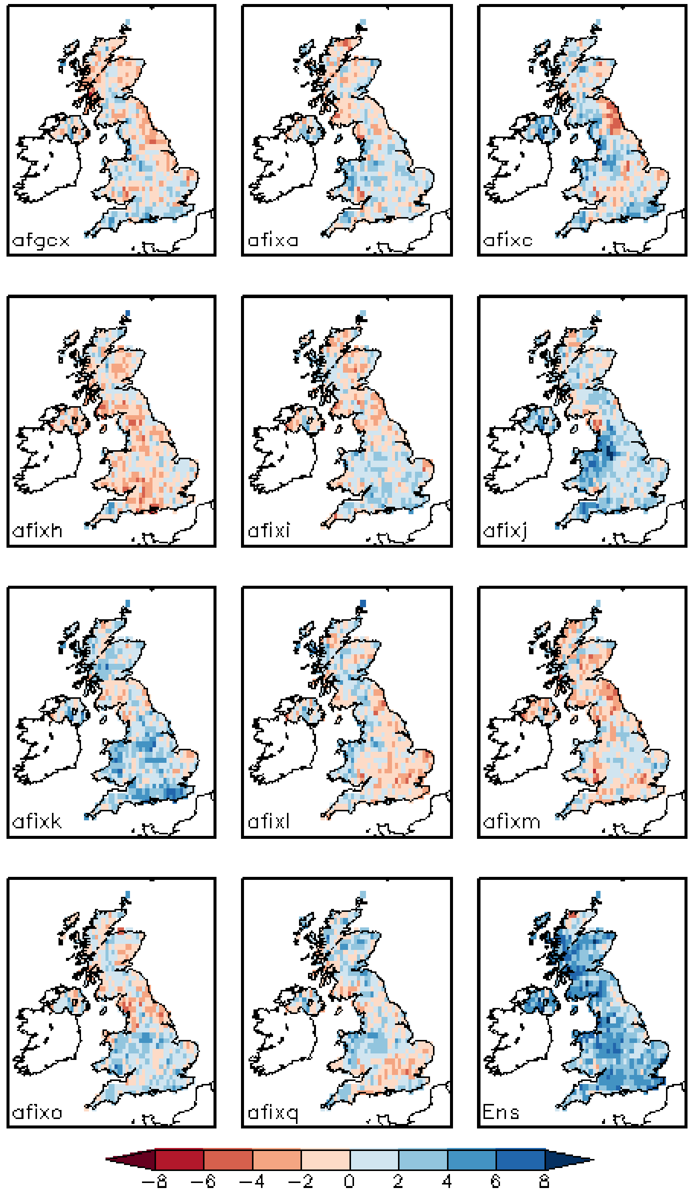

Figure 6.9: Bias in frequency of drought events at a given duration (*FDD*) for extreme droughts with persistence of at least 3 months (FDD_3) for each of the 11-member ensemble (afgcx to afixq). Color bar shows the absolute change relative to the observed data. Ens refers to the ensemble mean bias.

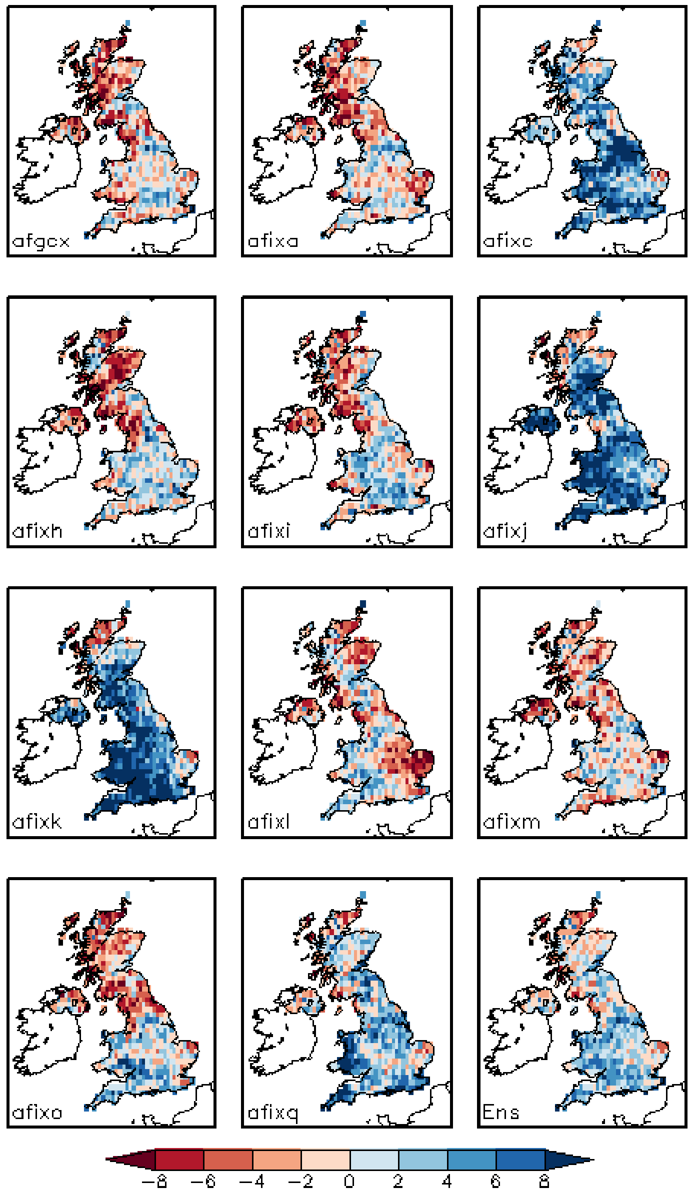

Figure 6.10: As Figure 6.9, but for moderate droughts.

Table 6.1: 11 members of the HadRM3-PPE-UK and their climate sensitivities (K) of corresponding HadSM3 variant. Source: Met Office (2008)

Model	Climate sensitivity (K)
afgcx	3.53485
afixa	2.58475
afixc	2.81543
afixh	3.43839
afixi	4.39594
afixj	3.89523
afixk	4.44284
afixl	4.88248
afixm	4.54486
afixo	4.79648
afixq	7.11014

Table 6.2: Regionally averaged bias in mean seasonal rainfall (*msRAIN*) for the 23 WRRs during the dry and wet seasons. Data show the ensemble maximum (Max), minimum (Min) and mean (Mn), expressed as percentage change relative to the observed data, and the number of models showing positive (Ps) and negative (Ng) bias. The ensemble spread (Spr) is expressed as the difference between the ensemble maximum and ensemble minimum.

	Dry season						Wet season					
	Max	Min	Spr	Mn	Ps	Ng	Max	Min	Spr	Mn	Ps	Ng
England												
- ANG	28.9	-22.9	51.8	4.6	7	4	32.6	14.9	17.7	23.3	11	0
- HUM	23.9	-26.6	50.5	-0.7	5	6	17.5	0.9	16.6	9.3	11	0
- NHM	17.3	-27.1	44.4	-3.5	5	6	3.4	-10.5	13.9	-3.4	3	8
- NW.E	11.7	-30.1	41.8	-6.0	4	7	23.0	0.7	22.3	11.3	11	0
- SE.E	13.4	-36.4	49.8	-11.7	3	8	13.2	-4.7	17.9	1.6	6	5
- SEV	12.2	-36.0	48.2	-10.7	3	8	14.8	-4.8	19.6	4.7	8	3
- SW.E	16.0	-32.5	48.5	-7.9	4	7	15.6	-3.0	18.6	4.4	9	2
- THA	21.8	-30.7	52.5	-3.5	4	7	20.6	3.7	16.9	11.5	11	0
Wales												
- DEE	20.9	-30.6	51.5	-4.6	5	6	6.8	-13.6	20.4	-2.2	3	8
- WW	13.3	-30.1	43.4	-5.7	4	7	21.6	-0.2	21.8	9.8	10	1
Scotland												
- ARG	23.1	-14.7	37.8	5.1	7	4	13.8	-8.3	22.1	1.9	6	5
- CLY	8.9	-25.4	34.3	-5.5	5	6	5.9	-12.1	18.0	-2.7	4	7
- FOR	13.9	-25.7	39.6	-3.9	4	7	5.5	-10.4	15.9	-2.3	5	6
- NE.S	18.4	-19.5	37.9	1.1	6	5	-1.7	-18.8	17.1	-10.3	0	11
- NH	-2.7	-30.3	27.6	-15	0	11	-29.1	-39.0	9.9	-35	0	11
- O&S	12.8	-2.4	15.2	5.3	10	1	2.2	-12.6	14.8	-3.5	4	7
- SOL	9.6	-27.2	36.8	-5.3	5	6	17.3	-3.7	21.0	7.0	10	1
- TAY	20.5	-25.2	45.7	-1.6	5	6	5.3	-11.8	17.1	-4.0	3	8
- TW	13.3	-26.4	39.7	-4.8	5	6	-2.0	-15.8	13.8	-7.9	0	11
- WH	6.0	-24.5	30.5	-8.8	2	9	-14.2	-28.9	14.7	-21.7	0	11
N. Ireland												
- NB	13.5	-24.9	38.4	-2.5	5	6	7.0	-4.4	11.4	1.0	7	4
- NE.I	-5.5	-38.1	32.6	-17.6	0	11	-11.3	-22.0	10.7	-16.9	0	11
- NW.I	5.9	-28.7	34.6	-9.5	3	8	-2.3	-15.9	13.6	-9.3	0	11

Abbreviations:
(England) ANG – Anglian; HUM – Humber; NHM – Northumbria; NW.E – NW England; SE.E – SE England; SEV – Severn; SW.E – SW England; THA – Thames; **(Wales)** DEE – Dee; WW – W Wales; **(Scotland)** ARG – Argyll; CLY – Clyde; FOR – Forth; NE.S – NE Scotland; NH – N Highland; O&S – Orkney & Shetland; SOL – Solway; TAY – Tay; TW – Tweed; WH – W Highland; **(N. Ireland)** NB – Neagh Bann; NE.I – NE Ireland; NW.I – NW Ireland

Table 6.3: As Table 6.2, but for mean seasonal DSI6 (*msDSI6*).

	Dry season						Wet season					
	Max	Min	Spr	Mn	Ps	Ng	Max	Min	Spr	Mn	Ps	Ng
England												
- ANG	10.4	-44.6	55.0	-29.3	1	10	98.6	-9.9	108.5	47.2	9	2
- HUM	-11.2	-51.4	40.2	-33.4	0	11	62.8	-13.9	76.7	23.2	9	2
- NHM	16.2	-33.4	49.6	-12.3	3	8	73.5	18.1	55.4	43.1	11	0
- NW.E	-5.3	-49.5	44.2	-33.3	0	11	65.5	0.7	64.8	31.0	11	0
- SE.E	-8.3	-45.3	37.0	-27.8	0	11	80.5	2.8	77.7	44.7	11	0
- SEV	-8.3	-35.0	26.7	-20.7	0	11	131.9	7.8	124.1	70.7	11	0
- SW.E	1.4	-27.2	28.6	-16.6	1	10	108.5	14.1	94.4	60.4	11	0
- THA	-5.9	-44.3	38.4	-32.2	0	11	105.1	-6.0	111.1	48.3	9	2
Wales												
- DEE	-25.7	-42.2	16.5	-33.0	0	11	82.1	1.5	80.6	42.5	11	0
- WW	-6.7	-45.6	38.9	-27.8	0	11	84.1	9.6	74.5	44.2	11	0
Scotland												
- ARG	15.7	-29.8	45.5	-9.7	2	9	60.3	-7.8	68.1	31.0	9	2
- CLY	6.8	-47.1	53.9	-24.0	1	10	59.9	-1.0	60.9	29.3	10	1
- FOR	-1.0	-47.6	46.6	-25.1	0	11	48.4	-6.2	54.6	22.2	9	2
- NE.S	13.8	-30.4	44.2	-8.9	3	8	63.0	-10.0	73.0	37.8	10	1
- NH	15.2	-38.6	53.8	-19.1	2	9	43.0	-17.6	60.6	15.9	7	4
- O&S	-28.0	-56.8	28.8	-45.0	0	11	14.1	-31.3	45.4	-5.2	4	7
- SOL	17.5	-41.8	59.3	-20.8	1	10	82.3	17.7	64.6	46.0	11	0
- TAY	4.7	-37.9	42.6	-15.4	1	10	56.5	10.8	45.7	34.7	11	0
- TW	15.7	-42.4	58.1	-17.1	3	8	68.5	-4.2	72.7	30.4	10	1
- WH	-4.7	-43.6	38.9	-26.3	0	11	24.2	-39.4	63.6	-4.5	5	6
N. Ireland												
- NB	-3.2	-49.5	46.3	-25.2	0	11	60.9	1.5	59.4	27.5	11	0
- NE.I	23.8	-45.6	69.4	-13.1	2	8	51.4	11.7	39.7	31.1	11	0
- NW.I	-8.4	-44.8	36.4	-27.5	0	11	59.3	-6.6	65.9	28.6	10	1

Abbreviations:
(England) ANG – Anglian; HUM – Humber; NHM – Northumbria; NW.E – NW England; SE.E – SE England; SEV – Severn; SW.E – SW England; THA – Thames; **(Wales)** DEE – Dee; WW – W Wales; **(Scotland)** ARG – Argyll; CLY – Clyde; FOR – Forth; NE.S – NE Scotland; NH – N Highland; O&S – Orkney & Shetland; SOL – Solway; TAY – Tay; TW – Tweed; WH – W Highland; **(N. Ireland)** NB – Neagh Bann; NE.I – NE Ireland; NW.I – NW Ireland

Table 6.4: Loadings of the first ten principal components (PC) for the 11-member ensemble (afgcx to afixq) and the observed (obs) data for a) mean seasonal rainfall (*msRAIN*) and b) mean seasonal DSI6 (*msDSI6*) during the dry season.

	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6	PC 7	PC 8	PC 9	PC 10
a) *msRAIN*										
afgcx	83.9	4.6	2.5	1.9	1.2	1.0	0.7	0.6	0.5	0.4
afixa	86.4	5.2	1.9	1.2	1.0	0.8	0.5	0.4	0.3	0.3
afixc	84.9	4.3	2.9	1.5	1.4	0.9	0.6	0.5	0.4	0.4
afixh	87.0	3.9	2.0	1.3	1.0	0.7	0.6	0.5	0.4	0.3
afixi	90.2	2.9	1.8	1.2	0.7	0.5	0.4	0.3	0.2	0.2
afixj	91.1	2.8	1.6	0.8	0.6	0.6	0.4	0.3	0.2	0.2
afixk	89.3	4.1	1.5	1.1	0.6	0.6	0.4	0.3	0.3	0.2
afixl	90.5	2.6	1.8	0.9	0.8	0.6	0.4	0.4	0.3	0.2
afixm	90.7	3.0	1.4	0.9	0.8	0.5	0.4	0.3	0.3	0.2
afixo	85.9	3.3	2.8	1.8	1.2	0.8	0.7	0.5	0.4	0.3
afixq	93.0	2.1	1.3	0.9	0.6	0.4	0.3	0.3	0.2	0.1
obs	86.6	3.7	1.4	1.1	1.0	0.8	0.6	0.5	0.4	0.3
b) *msDSI6*										
afgcx	24.0	13.1	8.4	6.7	5.6	5.0	3.9	2.9	2.5	2.3
afixa	19.7	10.4	9.3	8.1	5.3	4.4	4.2	3.3	2.9	2.3
afixc	21.5	10.6	9.7	6.5	5.3	4.2	3.4	3.2	2.9	2.7
afixh	17.3	14.0	9.0	7.1	6.0	5.2	4.3	3.6	3.2	2.6
afixi	22.1	11.5	8.8	7.7	6.0	4.9	4.5	3.6	2.4	2.2
afixj	29.4	9.0	8.5	6.2	4.8	3.8	3.2	2.6	2.5	2.4
afixk	21.4	11.2	8.3	7.2	6.3	4.4	4.1	3.2	2.8	2.5
afixl	28.3	11.4	8.9	6.7	5.7	3.8	3.6	2.6	2.3	2.1
afixm	22.1	12.8	8.3	8.1	6.7	4.0	3.8	3.0	2.6	2.5
afixo	23.6	14.5	8.0	6.2	4.9	4.0	3.4	2.9	2.6	2.2
afixq	16.1	13.0	10.5	9.7	6.2	4.6	4.2	3.0	2.8	2.6
obs	24.5	8.0	6.5	6.2	4.5	4.2	3.5	2.8	2.6	2.4

Table 6.5: As Table 6.4, but for the wet season.

	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6	PC 7	PC 8	PC 9	PC 10
a) *msRAIN*										
afgcx	92.4	3.1	1.1	0.8	0.6	0.3	0.3	0.2	0.2	0.1
afixa	91.5	3.1	1.7	1.1	0.6	0.3	0.3	0.3	0.2	0.1
afixc	93.4	2.2	1.2	0.8	0.6	0.3	0.2	0.2	0.2	0.1
afixh	92.8	2.7	1.2	0.8	0.7	0.3	0.2	0.2	0.2	0.1
afixi	93.7	2.9	0.8	0.7	0.5	0.2	0.2	0.2	0.1	0.1
afixj	91.5	4.0	1.3	0.8	0.3	0.3	0.3	0.2	0.2	0.1
afixk	94.5	2.1	0.9	0.6	0.3	0.3	0.2	0.2	0.2	0.1
afixl	91.7	4.2	1.0	0.8	0.5	0.3	0.2	0.2	0.2	0.1
afixm	93.6	2.8	0.8	0.6	0.5	0.3	0.2	0.2	0.2	0.1
afixo	92.2	3.4	1.1	0.8	0.5	0.4	0.3	0.2	0.2	0.1
afixq	95.3	2.1	0.6	0.4	0.3	0.3	0.2	0.1	0.1	0.1
obs	93.5	2.4	0.8	0.7	0.5	0.3	0.2	0.2	0.1	0.1
b) *msDSI6*										
afgcx	23.4	13.7	8.2	7.5	6.5	5.6	3.9	3.2	2.5	2.2
afixa	24.1	10.6	9.0	7.7	5.7	5.0	3.8	3.4	2.6	2.3
afixc	21.4	13.5	9.6	6.8	6.2	5.2	3.9	3.8	3.2	2.4
afixh	18.8	11.8	8.8	7.6	5.6	5.4	4.5	3.9	3.1	2.6
afixi	22.3	13.3	10.0	9.0	5.6	4.5	4.1	3.3	2.7	2.3
afixj	34.2	12.0	9.0	7.5	4.9	3.6	3.1	2.9	2.3	2.1
afixk	27.7	14.7	9.1	7.7	6.1	4.1	3.6	2.8	2.5	2.1
afixl	25.3	12.6	9.7	7.3	5.3	4.3	4.0	3.3	3.2	2.2
afixm	22.0	12.9	11.0	7.2	5.6	4.3	3.8	3.5	3.0	2.8
afixo	22.4	14.2	9.2	7.9	5.8	4.2	3.4	3.1	2.7	2.3
afixq	24.3	17.4	9.6	7.8	5.6	4.5	3.6	3.1	2.2	2.0
obs	20.0	10.3	7.5	5.6	5.3	4.3	3.7	3.0	2.7	2.5

Table 6.6: Regionally-averaged bias in drought intensity (*DI*) for the 23 WRRs during the (a) dry and (b) wet seasons under moderate and extreme drought conditions. Data show the ensemble maximum (Max), minimum (Min) and mean (Mn), expressed as percentage change relative to the observed data, and the number of models showing positive (Ps) and negative (Ng) bias. The ensemble spread (Spr) is expressed as the difference between the ensemble maximum and ensemble minimum.

	Moderate droughts						Extreme droughts					
	Max	Min	Spr	Mn	Ps	Ng	Max	Min	Spr	Mn	Ps	Ng
a) Dry season												
England												
- ANG	0.8	-56.8	57.6	-30.4	1	10	25.9	-34.8	60.7	-20.5	1	10
- HUM	-9.7	-52.3	42.6	-33.1	0	11	-0.1	-41.2	41.1	-24.6	0	11
- NHM	19.9	-36.4	56.3	-11.0	3	8	36.5	-23.3	59.8	-1.2	4	7
- NW.E	-13.1	-60.3	47.2	-36.1	0	11	10.1	-35.0	45.1	-18.3	2	9
- SE.E	-13.9	-44.7	30.8	-28.9	0	11	2.3	-32.5	34.8	-18.4	1	10
- SEV	-1.3	-39.2	37.9	-22.6	0	11	5.1	-24.6	29.7	-8.1	4	6
- SW.E	3.5	-28.8	32.3	-13.3	1	10	20.7	-19.4	40.1	-4.8	4	7
- THA	-16.1	-54.3	38.2	-34.3	0	11	4.4	-40.3	44.7	-25.7	1	10
Wales												
- DEE	-12.5	-46.8	34.3	-31.0	0	11	-11	-38.7	28.1	-22.2	0	11
- WW	0.9	-43.7	44.6	-23.0	1	10	0.3	-32.9	33.2	-17.3	1	10
Scotland												
- ARG	16.4	-21.5	37.9	-8.4	3	8	33.6	-20.0	53.6	0.9	4	7
- CLY	5.1	-49.4	54.5	-28.0	1	10	27.5	-33.7	61.2	-7.8	3	8
- FOR	20.0	-38.5	58.5	-16.7	1	10	16.6	-31.2	47.8	-9.3	4	7
- NE.S	25.5	-26.0	51.5	-5.3	3	8	26.8	-20.5	47.3	2.6	6	5
- NH	27.5	-39.3	66.8	-20.3	2	9	31.0	-22.5	53.5	-3.8	5	6
- O&S	-27.7	-53.3	25.6	-42.7	0	11	-15.0	-47.7	32.7	-34.3	0	11
- SOL	8.2	-52.1	60.3	-24.3	1	10	38.6	-29.0	67.6	-4.4	3	8
- TAY	3.7	-40.8	44.5	-18.3	1	10	12.2	-26.9	39.1	-7	4	7
- TW	26.9	-33.3	60.2	-11.5	3	8	29.9	-28.9	58.8	-2.9	4	7
- WH	1.9	-40.7	42.6	-21.1	1	10	4.7	-37.8	42.5	-19.8	1	10
N. Ireland												
- NB	2.6	-43.6	46.2	-22.1	1	10	6.5	-39.3	45.8	-12.6	2	9
- NE.I	25.6	-41.7	67.3	-13.0	2	9	15.8	-39.9	55.7	-6.7	4	7
- NW.I	-16.9	-53.4	36.5	-31.3	0	11	12.9	-36.4	49.3	-14.0	2	9
(b) Wet season												
England												
- ANG	205.6	18.3	187.3	97.5	11	0	60.9	-21.3	82.2	17.6	9	2
- HUM	142.0	1.6	140.4	67.1	11	0	22.2	-24.9	47.1	1.3	5	6
- NHM	166.5	47.8	118.7	103.1	11	0	52.1	2.5	49.6	20.6	11	0
- NW.E	566.6	241.1	325.5	377.6	11	0	30.9	-12.3	43.2	10.4	9	2
- SE.E	123.2	11.6	111.6	60.6	11	0	32.9	-13.5	46.4	14.7	9	2
- SEV	222.8	29.0	193.8	117.7	11	0	60.4	-7.5	67.9	33.9	10	1
- SW.E	148.9	26.6	122.3	79.4	11	0	50.3	-1.8	52.1	27.2	10	1
- THA	189.3	11.7	177.6	87.4	11	0	38.1	-23.2	61.3	14.2	8	3
Wales												
- DEE	160.7	28.3	132.4	87.4	11	0	32.7	-17.2	49.9	12.2	9	2
- WW	166.1	47.1	119.0	105.0	11	0	34.1	-8.5	42.6	14.4	10	1

Scotland												
- ARG	219.4	-1.3	220.7	135.5	10	1	41.5	-7.8	49.3	17.1	8	3
- CLY	135.0	18.8	116.2	76.9	11	0	44.7	-11.7	56.4	10.9	8	3
- FOR	167.0	23.8	143.2	95.5	11	0	34.8	-15.6	50.4	7.5	7	4
- NE.S	252.4	71.4	181.0	169.3	11	0	36.0	-19.7	55.7	11.2	10	1
- NH	103.5	-0.9	104.4	47.4	10	1	28.9	-24.9	53.8	-0.3	7	4
- O&S	37.8	-25.1	62.9	8.9	7	4	4.5	-32.5	37.0	-15.3	1	10
- SOL	154.2	47.1	107.1	92.7	11	0	52.1	0.3	51.8	20.1	11	0
- TAY	121.5	22.7	98.8	68.1	11	0	28.0	-13.9	41.9	8.6	9	2
- TW	156.2	30.8	125.4	93.1	11	0	51.2	-18.6	69.8	12.4	7	4
- WH	52.6	-50.8	103.4	8.0	7	4	10.8	-33.6	44.4	-10.7	4	7
N. Ireland												
- NB	108.4	5.4	103.0	48.2	11	0	35.5	-1.3	36.8	16.9	10	1
- NE.I	70.7	11.2	59.5	39.9	11	0	33.5	-0.1	33.6	16.7	10	1
- NW.I	130.1	3.8	126.3	67.5	11	0	33.7	-10.2	43.9	8.8	8	3

Abbreviations:
(England) ANG – Anglian; HUM – Humber; NHM – Northumbria; NW.E – NW England; SE.E – SE England; SEV – Severn; SW.E – SW England; THA – Thames; **(Wales)** DEE – Dee; WW – W Wales; **(Scotland)** ARG – Argyll; CLY – Clyde; FOR – Forth; NE.S – NE Scotland; NH – N Highland; O&S – Orkney & Shetland; SOL – Solway; TAY – Tay; TW – Tweed; WH – W Highland; **(N. Ireland)** NB – Neagh Bann; NE.I – NE Ireland; NW.I – NW Ireland

Table 6.7: Regionally-averaged bias in drought covariance index (*CI*) for the 23 WRRs during the (a) dry and (b) wet seasons under moderate and extreme drought conditions. Data show the ensemble maximum (Max), minimum (Min) and mean (Mn), expressed as percentage change relative to the observed data, and the number of models showing positive (Ps) and negative (Ng) bias. The ensemble spread (Spr) is expressed as the difference between the ensemble maximum and ensemble minimum.

	Moderate droughts						Extreme droughts					
	Max	Min	Spr	Mn	Ps	Ng	Max	Min	Spr	Mn	Ps	Ng
a) Dry season												
England												
- ANG	24.5	1.4	23.1	12.8	11	0	63.3	4.9	58.4	29.7	11	0
- HUM	28.8	2.3	26.5	13.7	11	0	58.6	-0.1	58.7	28.5	10	1
- NHM	22.5	-5.8	28.3	2.3	4	7	48.1	-24.9	73.0	-2.3	5	6
- NW.E	30.6	-4.2	34.8	13.2	10	1	55.0	-11.3	66.3	17.2	8	3
- SE.E	29.1	-3.4	32.5	17.9	10	1	70.6	-11.2	81.8	31.1	9	2
- SEV	30.4	3.7	26.7	16.1	11	0	64.8	0.1	64.7	30.6	11	0
- SW.E	26.3	5.0	21.3	16.1	11	0	56.1	-1.1	57.2	31.1	10	1
- THA	29.4	5.6	23.8	18.7	11	0	69.2	0.7	68.5	35.8	11	0
Wales												
- DEE	27.3	1.2	26.1	12.1	11	0	86.4	-8.0	94.4	40.6	10	1
- WW	32.3	4.4	27.9	15.9	11	0	75.6	7.4	68.2	35.1	11	0
Scotland												
- ARG	20.8	-12.5	33.3	3.7	6	5	64.3	-0.2	64.5	29.0	10	1
- CLY	30.1	-1.2	31.3	10.1	10	1	47.7	-7.6	55.3	14.8	8	3
- FOR	23.6	-6.1	29.7	3.7	6	5	56.5	-9.7	66.2	17.3	9	2
- NE.S	19.4	-9.8	29.2	1.9	6	5	33.4	-24.0	57.4	-1.2	5	6
- NH	19.1	-14.4	33.5	0.4	7	4	28.5	-13.2	41.7	0.7	6	5
- O&S	9.7	-11.3	21.0	0.0	6	5	82.1	-0.9	83.0	27.2	9	1
- SOL	25.2	-11.9	37.1	6.2	8	3	48.8	-13.5	62.3	16.3	8	3
- TAY	30.7	-5.2	35.9	7.4	9	2	86.9	-1.5	88.4	32.4	10	1
- TW	23.3	-8.7	32.0	2.4	5	6	58.5	-29.5	88.0	10.5	7	4
- WH	13.0	-12.4	25.4	-0.7	4	7	80.7	2.7	78.0	34.8	11	0
N. Ireland												
- NB	37.6	0.3	37.3	12.0	11	0	98.6	3.6	95.0	36.6	11	0
- NE.I	30.2	-13.1	43.3	4.3	7	4	75.3	-11.4	86.7	20.5	8	3
- NW.I	43.1	2.3	40.8	16.4	11	0	96.6	-6.6	103.2	30.6	10	1
b) Wet season												
England												
- ANG	3.4	-6.5	9.9	-1.9	4	7	27.1	-11.1	38.2	3.5	5	6
- HUM	9.4	-1.9	11.3	2.8	9	2	39.9	-4.3	44.2	15.0	9	2
- NHM	4.4	-9.5	13.9	-1.1	5	6	10.2	-23.4	33.6	-7.2	4	7
- NW.E	5.5	-3.6	9.1	1.4	6	4	43.3	-6.8	50.1	19.7	9	1
- SE.E	6.6	-5.3	11.9	2.7	9	2	29.9	-24.4	54.3	-2.5	4	7
- SEV	6.2	-3.5	9.7	0.4	6	5	38.7	-7.8	46.5	11.9	9	2
- SW.E	5.9	-3.2	9.1	1.5	8	3	48.5	-2.4	50.9	15.8	10	1
- THA	9.9	-3.7	13.6	0.7	6	4	36.8	-16.1	52.9	3.6	6	5
Wales												
- DEE	6.5	-4.9	11.4	0.3	5	6	41.0	-14.3	55.3	19.3	10	1
- WW	9.2	-0.4	9.6	5.2	9	1	41.3	-6.6	47.9	20.2	10	1

Scotland												
- ARG	4.7	-10.5	15.2	-1.6	4	7	40.7	-23.5	64.2	10.8	7	4
- CLY	8.2	-8.0	16.2	-1.6	3	7	19.0	-11.0	30.0	6.4	9	2
- FOR	2.2	-7.3	9.5	-2.5	2	9	32.9	-8.2	41.1	14.5	10	1
- NE.S	-3.5	-9.7	6.2	-6.8	0	11	21.4	-21.5	42.9	-4.1	4	7
- NH	2.6	-6.3	8.9	-2.3	2	8	12.4	-19.1	31.5	-0.8	6	5
- O&S	8.8	-10.8	19.6	-3.0	3	8	31.0	-23.6	54.6	-0.7	4	7
- SOL	7.0	-7.3	14.3	0.2	5	6	15.9	-13.7	29.6	4.2	8	3
- TAY	6.1	-1.7	7.8	2.1	6	5	20.5	-12.1	32.6	4.1	6	5
- TW	4.5	-9.4	13.9	-1.9	4	7	20.0	-24.4	44.4	0.3	5	6
- WH	6.4	-8.5	14.9	-1.1	6	5	29.2	-20.3	49.5	5.6	7	4
N. Ireland												
- NB	7.1	-6.8	13.9	-0.9	5	6	58.7	9.4	49.3	30.8	11	0
- NE.I	11.6	-6.4	18.0	2.3	8	3	47.2	-14.9	62.1	16.5	10	1
- NW.I	12.3	-2.9	15.2	3.3	9	2	49.9	10.3	39.6	32.3	11	0

Abbreviations:
(England) ANG – Anglian; HUM – Humber; NHM – Northumbria; NW.E – NW England; SE.E – SE England; SEV – Severn; SW.E – SW England; THA – Thames; **(Wales)** DEE – Dee; WW – W Wales; **(Scotland)** ARG – Argyll; CLY – Clyde; FOR – Forth; NE.S – NE Scotland; NH – N Highland; O&S – Orkney & Shetland; SOL – Solway; TAY – Tay; TW – Tweed; WH – W Highland; **(N. Ireland)** NB – Neagh Bann; NE.I – NE Ireland; NW.I – NW Ireland

Table 6.8: Regionally-averaged bias in frequency of drought months (*FDM*) for the 23 WRRs during the (a) dry and (b) wet seasons under moderate and extreme drought conditions. Data show the ensemble maximum (Max), minimum (Min) and mean (Mn), expressed as percentage change relative to the observed data, and the number of models showing positive (Ps) and negative (Ng) bias. The ensemble spread (Spr) is expressed as the difference between the ensemble maximum and ensemble minimum.

	Moderate droughts						Extreme droughts					
	Max	Min	Spr	Mn	Ps	Ng	Max	Min	Spr	Mn	Ps	Ng
a) Dry season												
England												
- ANG	-16.1	-47.7	31.6	-31.4	0	11	-14.4	-59.1	44.7	-33.0	0	11
- HUM	-4.9	-45.2	40.3	-28.6	0	11	-0.2	-56.0	55.8	-28.8	0	11
- NHM	-5.3	-41.4	36.1	-23.3	0	11	10.1	-51.4	61.5	-16.9	1	10
- NW.E	-15.0	-47.2	32.2	-32.0	0	11	-9.5	-50.7	41.2	-30.1	0	11
- SE.E	-19.5	-46.7	27.2	-35.3	0	11	-13.7	-66.6	52.9	-39.5	0	11
- SEV	-21.6	-51.0	29.4	-36.4	0	11	-13.7	-68.5	54.8	-37.7	0	11
- SW.E	-21.7	-46.4	24.7	-34.0	0	11	-14.1	-64.5	50.4	-38.5	0	11
- THA	-18.0	-50.4	32.4	-34.8	0	11	-15.2	-62.8	47.6	-38.8	0	11
Wales												
- DEE	-22.2	-50.5	28.3	-37.1	0	11	-16.5	-67.5	51.0	-41.4	0	11
- WW	-22.9	-49.7	26.8	-35.3	0	11	-19.0	-67.2	48.2	-39.9	0	11
Scotland												
- ARG	4.1	-29.9	34.0	-14.9	2	9	0.6	-24.4	25.0	-15.0	1	10
- CLY	-14.5	-41.4	26.9	-25.8	0	11	-5.9	-39.4	33.5	-19.5	0	11
- FOR	-5.8	-42.5	36.7	-25.6	0	11	11.8	-39.8	51.6	-16.2	1	10
- NE.S	-9.0	-39.0	30.0	-21.4	0	11	12.0	-36.2	48.2	-8.1	3	8
- NH	-2.0	-31.7	29.7	-16.5	0	11	6.1	-27.8	33.9	-3.4	6	5
- O&S	-12.8	-30.6	17.8	-22.2	0	11	-18.6	-40.7	22.1	-28.9	0	11
- SOL	-13.9	-46.2	32.3	-28.9	0	11	-7.4	-44.7	37.3	-23.3	0	11
- TAY	-10.4	-41.9	31.5	-24.6	0	11	3.2	-59.8	63.0	-18.0	1	10
- TW	-2.0	-42.7	40.7	-23.3	0	11	18.4	-44.3	62.7	-14.4	2	9
- WH	13.7	-21.9	35.6	-6.9	2	9	5.6	-25.3	30.9	-7.6	2	9
N. Ireland												
- NB	-2.5	-41.7	39.2	-22.3	0	11	-4.0	-64.2	60.2	-28.8	0	11
- NE.I	4.4	-34.5	38.9	-17.5	1	10	5.6	-60.2	65.8	-22.6	1	10
- NW.I	-8.5	-44.9	36.4	-25.0	0	11	2.5	-60.9	63.4	-25.2	1	10
b) Wet season												
England												
- ANG	67.5	23.2	44.3	44.7	11	0	78.6	20.8	57.8	44.9	11	0
- HUM	60.6	6.7	53.9	38.3	11	0	66.2	3.8	62.4	35.3	11	0
- NHM	54.6	7.1	47.5	30.8	11	0	58.8	-6.3	65.1	21.2	10	1
- NW.E	71.9	23.1	48.8	48.8	11	0	57.9	12.2	45.7	36.1	11	0
- SE.E	51.8	21.8	30.0	39.4	11	0	70.1	14.9	55.2	41.8	11	0
- SEV	63.0	26.4	36.6	45.1	11	0	76.3	15.4	60.9	43.5	11	0
- SW.E	46.0	21.8	24.2	33.7	11	0	57.5	14.6	42.9	35.2	11	0
- THA	63.2	23.2	40.0	44.0	11	0	83.7	20.6	63.1	52.2	11	0
Wales												
- DEE	59.6	26.2	33.4	43.6	11	0	70.2	17.6	52.6	43.2	11	0
- WW	61.1	28.4	32.7	43.6	11	0	68.6	21.1	47.5	42.1	11	0

Scotland											
- ARG	38.7	-5.6	44.3	19.1	9	2	28.9	-0.6	29.5	17.8	10	1
- CLY	60.4	22.0	38.4	37.8	11	0	42.8	6.8	36.0	21.5	11	0
- FOR	66.3	9.4	56.9	39.8	11	0	43.4	-12.7	56.1	17.8	10	1
- NE.S	56.2	13.3	42.9	31.1	11	0	39.0	-11.3	50.3	9.8	8	3
- NH	40.2	3.3	36.9	21.1	11	0	28.5	-4.9	33.4	4.6	6	5
- O&S	38.8	16.2	22.6	28.0	11	0	45.9	20.8	25.1	32.0	11	0
- SOL	67.4	21.5	45.9	42.9	11	0	47.7	10.4	37.3	26.4	11	0
- TAY	50.4	12.4	38.0	29.5	11	0	57.3	-3.5	60.8	17.9	10	1
- TW	56.1	3.1	53.0	30.8	11	0	44.8	-17.4	62.2	14.6	9	2
- WH	26.2	-15.8	42.0	8.6	9	2	33.6	-5.0	38.6	11.2	10	1
N. Ireland												
- NB	51.3	4.1	47.2	27.8	11	0	80.3	6.1	74.2	36.4	11	0
- NE.I	39.9	-4.3	44.2	20.4	10	1	68.8	-5.3	74.1	26.7	10	1
- NW.I	57.0	12.1	44.9	32.5	11	0	63.2	-1.9	65.1	26.7	10	1

Abbreviations:
(England) ANG – Anglian; HUM – Humber; NHM – Northumbria; NW.E – NW England; SE.E – SE England; SEV – Severn; SW.E – SW England; THA – Thames; **(Wales)** DEE – Dee; WW – W Wales; **(Scotland)** ARG – Argyll; CLY – Clyde; FOR – Forth; NE.S – NE Scotland; NH – N Highland; O&S – Orkney & Shetland; SOL – Solway; TAY – Tay; TW – Tweed; WH – W Highland; **(N. Ireland)** NB – Neagh Bann; NE.I – NE Ireland; NW.I – NW Ireland

Table 6.9: Regionally-averaged bias in frequency of drought events at a given duration for moderate droughts (*FDD*) with persistence of at least 3 (FDD_3), 6 (FDD_6), 10 (FDD_{10}) and 12 (FDD_{12}) months for the 23 WRRs. Data show the ensemble maximum (Max), minimum (Min) and mean (Mn), expressed as absolute change relative to the observed data, and the number of models showing positive (Ps), negative (Ng) and no (No) bias. The ensemble spread (Spr) is expressed as the difference between the ensemble maximum and ensemble minimum.

	FDD_3							FDD_3						
	Max	Min	Spr	Mn	Ps	Ng	No	Max	Min	Spr	Mn	Ps	Ng	No
England														
- ANG	3.6	-5.6	9.2	0.5	7	4	0	5.7	0.4	5.3	2.9	11	0	0
- HUM	7.8	-0.5	8.3	3.0	10	1	0	3.6	0.1	3.5	2.0	11	0	0
- NHM	5.0	-3.5	8.5	0.4	5	6	0	2.6	-1.6	4.2	-0.1	5	6	0
- NW.E	8.2	-2.0	10.2	1.5	5	4	2	2.8	-0.4	3.2	1.5	9	1	1
- SE.E	11.0	0.6	10.4	4.1	11	0	0	3.3	-1.6	4.9	1.3	9	2	0
- SEV	11.3	-0.6	11.9	3.9	10	1	0	3.2	-0.6	3.8	1.7	9	2	0
- SW.E	9.7	-1.6	11.3	3.1	9	2	0	3.9	0.0	3.9	1.8	9	0	2
- THA	8.2	-0.3	8.5	3.5	10	1	0	3.6	0.2	3.4	2.0	11	0	0
Wales														
- DEE	11.8	1.0	10.8	5.1	11	0	0	5.5	0.5	5.0	3.8	11	0	0
- WW	11.0	-0.4	11.4	4.4	10	1	0	2.8	0.1	2.7	1.6	11	0	0
Scotland														
- ARG	2.7	-4.9	7.6	-2.3	2	9	0	2.0	-1.2	3.2	0.3	6	4	1
- CLY	8.1	-5.4	13.5	0.0	4	7	0	1.4	-2.6	4.0	-0.8	3	7	1
- FOR	8.7	-2.7	11.4	1.8	5	6	0	4.0	0.6	3.4	2.2	11	0	0
- NE.S	2.5	-4.7	7.2	-0.9	4	7	0	3.2	-0.6	3.8	1.6	10	1	0
- NH	1.2	-4.2	5.4	-1.5	3	8	0	1.9	-0.4	2.3	0.6	7	3	1
- O&S	4.0	-3.3	7.3	0.6	6	2	3	4.3	1.3	3.0	3.1	11	0	0
- SOL	8.8	-5.5	14.3	-0.9	4	7	0	2.3	-2.3	4.6	0.3	5	5	1
- TAY	8.4	-5.1	13.5	0.5	4	7	0	1.7	-0.9	2.6	0.7	9	2	0
- TW	8.0	-3.5	11.5	1.3	6	5	0	2.2	-2.2	4.4	0.5	8	3	0
- WH	3.6	-2.3	5.9	-0.2	3	8	0	3.7	0.2	3.5	1.6	11	0	0
N. Ireland														
- NB	9.8	-2.9	12.7	0.4	4	7	0	3.6	-1.7	5.3	1.2	10	1	0
- NE.I	9.2	-4.3	13.5	0.0	4	7	0	1.8	-2.2	4.0	-0.2	6	5	0
- NW.I	10.1	-4.3	14.4	0.3	3	8	0	3.1	-1.5	4.6	1.5	9	1	1

	FDD_{10}							FDD_{12}						
	Max	Min	Spr	Mn	Ps	Ng	No	Max	Min	Spr	Mn	Ps	Ng	No
England														
- ANG	2.6	-3.8	6.4	-0.7	4	7	0	1.5	-2.5	4.0	-1.0	2	9	0
- HUM	1.8	-4.5	6.3	-1.3	3	8	0	0.5	-4.1	4.6	-1.9	1	10	0
- NHM	1.3	-4.2	5.5	-0.6	5	5	1	2.3	-2.3	4.6	0.2	7	4	0
- NW.E	0.5	-4.2	4.7	-1.2	3	7	1	0.3	-3.2	3.5	-1.1	2	9	0
- SE.E	0.6	-4.9	5.5	-1.9	1	9	1	0.0	-4.0	4.0	-1.9	0	10	1
- SEV	1.2	-4.6	5.8	-1.6	1	10	0	0.2	-3.9	4.1	-1.8	1	10	0
- SW.E	0.3	-4.2	4.5	-1.8	1	10	0	0.7	-3.2	3.9	-1.6	1	9	1
- THA	0.4	-4.7	5.1	-1.9	1	10	0	-0.2	-4.2	4.0	-2.3	0	11	0

Wales														
- DEE	2.5	-4.2	6.7	-1.1	4	7	0	0.0	-4.2	4.2	-2.0	0	10	1
- WW	-0.1	-5.0	4.9	-2.4	0	11	0	0.2	-3.2	3.4	-1.5	1	10	0
Scotland														
- ARG	4.0	-0.8	4.8	1.4	8	3	0	2.8	-1.0	3.8	0.6	7	3	1
- CLY	3.0	-1.6	4.6	0.7	7	4	0	3.1	-1.0	4.1	1.0	7	4	0
- FOR	2.3	-2.1	4.4	0.3	6	5	0	1.6	-2.1	3.7	0.0	6	5	0
- NE.S	2.7	-2.0	4.7	0.6	8	3	0	1.8	-1.4	3.2	0.4	6	4	1
- NH	3.4	0.1	3.3	1.4	11	0	0	1.9	-0.4	2.3	0.7	9	2	0
- O&S	1.7	-2.0	3.7	-0.4	3	6	2	0.3	-2.0	2.3	-0.9	2	8	1
- SOL	2.1	-3.3	5.4	-0.2	5	6	0	2.4	-1.6	4.0	0.5	7	4	0
- TAY	1.6	-3.6	5.2	-0.3	6	4	1	0.9	-3.1	4.0	-0.6	6	4	1
- TW	1.6	-2.9	4.5	-0.2	7	4	0	2.4	-2.1	4.5	0.2	7	4	0
- WH	2.3	-2.3	4.6	0.0	4	7	0	1.4	-2.7	4.1	-0.7	3	8	0
N. Ireland														
- NB	3.1	-3.7	6.8	1.0	8	3	0	2.3	-2.6	4.9	0.5	7	4	0
- NE.I	4.0	-3.5	7.5	1.7	9	2	0	3.3	-2.8	6.1	1.0	7	3	1
- NW.I	2.7	-4.8	7.5	0.0	7	4	0	1.9	-3.5	5.4	-0.3	6	4	1

Abbreviations:
(England) ANG – Anglian; HUM – Humber; NHM – Northumbria; NW.E – NW England; SE.E – SE England; SEV – Severn; SW.E – SW England; THA – Thames; **(Wales)** DEE – Dee; WW – W Wales; **(Scotland)** ARG – Argyll; CLY – Clyde; FOR – Forth; NE.S – NE Scotland; NH – N Highland; O&S – Orkney & Shetland; SOL – Solway; TAY – Tay; TW – Tweed; WH – W Highland; **(N. Ireland)** NB – Neagh Bann; NE.I – NE Ireland; NW.I – NW Ireland

Table 6.10: As Table 6.9, but for extreme droughts.

	FDD_3							FDD_6						
	Max	Min	Spr	Mn	Ps	Ng	No	Max	Min	Spr	Mn	Ps	Ng	No
England														
- ANG	1.7	-0.8	2.5	0.8	10	1	0	0.7	-2.0	2.7	-0.3	4	6	1
- HUM	2.9	-0.4	3.3	1.1	10	1	0	1.0	-1.6	2.6	-0.2	3	8	0
- NHM	1.5	-2.5	4.0	-0.5	3	8	0	0.9	-1.3	2.2	0.0	4	6	1
- NW.E	3.7	-0.1	3.8	1.5	10	1	0	0.9	-1.3	2.2	0.1	7	4	0
- SE.E	4.6	-1.4	6.0	1.8	9	2	0	0.3	-2.5	2.8	-1.1	2	9	0
- SEV	2.8	-1.2	4.0	1.0	9	2	0	1.0	-2.2	3.2	-0.4	5	6	0
- SW.E	3.6	0.4	3.2	1.5	11	0	0	0.2	-2.4	2.6	-0.9	1	10	0
- THA	3.1	-1.0	4.1	0.9	7	4	0	0.3	-2.2	2.5	-0.8	1	10	0
Wales														
- DEE	5.2	-0.5	5.7	2.8	10	1	0	1.8	-2.2	4.0	-0.2	5	6	0
- WW	3.8	-0.5	4.3	1.9	10	1	0	0.4	-2.2	2.6	-0.7	2	7	2
Scotland														
- ARG	1.6	-2.1	3.7	0.4	8	2	1	2.1	-0.2	2.3	0.9	8	3	0
- CLY	1.8	-0.8	2.6	0.3	7	3	1	1.3	-0.9	2.2	0.3	7	4	0
- FOR	3.2	-0.2	3.4	1.4	10	1	0	2.0	0.2	1.8	0.9	11	0	0
- NE.S	2.9	-0.3	3.2	0.7	9	2	0	1.0	-0.8	1.8	0.4	9	2	0
- NH	1.3	-0.6	1.9	0.5	8	3	0	1.6	-0.5	2.1	0.5	9	2	0
- O&S	3.7	1.3	2.4	2.6	11	0	0	1.3	-1.0	2.3	0.4	7	1	3
- SOL	3.0	-1.6	4.6	0.1	5	6	0	0.9	-2.1	3.0	-0.4	3	8	0
- TAY	2.9	-0.6	3.5	0.7	7	3	1	1.8	-0.6	2.4	0.8	10	1	0
- TW	2.5	-1.0	3.5	0.8	8	3	0	1.7	-0.6	2.3	0.5	8	3	0
- WH	2.1	-0.1	2.2	1.1	10	1	0	1.4	-1.2	2.6	0.1	5	5	1
N. Ireland														
- NB	3.6	-0.4	4.0	1.5	9	2	0	2.2	-1.1	3.3	1.0	10	1	0
- NE.I	3.2	-0.2	3.4	1.5	9	1	1	2.2	-1.7	3.9	1.0	10	1	0
- NW.I	3.2	-1.4	4.6	0.7	8	3	0	1.2	-1.2	2.4	0.4	9	2	0

	FDD_{10}							FDD_{12}						
	Max	Min	Spr	Mn	Ps	Ng	No	Max	Min	Spr	Mn	Ps	Ng	No
England														
- ANG	0.4	-1.2	1.6	-0.4	2	8	1	0.7	-0.7	1.4	-0.2	2	7	2
- HUM	0.2	-1.9	2.1	-0.9	1	10	0	0.4	-1.3	1.7	-0.6	1	9	1
- NHM	1.2	-0.9	2.1	0.3	8	3	0	0.8	-0.9	1.7	0.3	8	3	0
- NW.E	0.4	-1.5	1.9	-0.7	3	8	0	0.2	-1.4	1.6	-0.6	1	10	0
- SE.E	0.0	-2.0	2.0	-1.0	0	9	2	0.3	-0.9	1.2	-0.3	4	7	0
- SEV	0.2	-1.7	1.9	-0.8	2	8	1	0.3	-1.1	1.4	-0.4	3	8	0
- SW.E	0.4	-1.8	2.2	-0.8	2	9	0	0.6	-1.0	1.6	-0.3	3	7	1
- THA	-0.1	-1.8	1.7	-0.8	0	11	0	0.8	-0.7	1.5	-0.1	4	7	0
Wales														
- DEE	-0.5	-3.5	3.0	-2.3	0	11	0	0.0	-1.5	1.5	-0.8	0	9	2
- WW	0.5	-1.9	2.4	-1.0	1	10	0	0.5	-1.4	1.9	-0.8	1	10	0

Scotland														
- ARG	1.3	-1.2	2.5	0.0	6	3	2	0.7	-1.0	1.7	0.0	6	4	1
- CLY	1.1	-0.5	1.6	0.2	5	6	0	1.2	-0.5	1.7	0.1	6	5	0
- FOR	0.3	-1.7	2.0	-0.5	3	7	1	0.7	-1.3	2.0	-0.2	4	7	0
- NE.S	0.6	-1.6	2.2	-0.3	4	7	0	0.2	-1.5	1.7	-0.5	2	9	0
- NH	0.5	-0.7	1.2	0.0	6	5	0	0.5	-0.8	1.3	-0.1	5	5	1
- O&S	0.0	-1.7	1.7	-0.7	0	9	2	0.3	-1.3	1.6	-0.4	1	7	3
- SOL	1.1	-1.2	2.3	0.0	4	7	0	1.0	-0.6	1.6	0.2	7	4	0
- TAY	0.2	-1.8	2.0	-0.8	1	10	0	0.4	-1.0	1.4	-0.3	4	6	1
- TW	0.6	-1.5	2.1	-0.2	4	6	1	0.8	-1.5	2.3	-0.2	3	7	1
- WH	0.7	-1.2	1.9	-0.4	3	8	0	0.8	-0.9	1.7	-0.3	2	8	1
N. Ireland														
- NB	0.7	-1.5	2.2	-0.2	6	5	0	0.8	-1.1	1.9	-0.2	4	7	0
- NE.I	1.0	-1.8	2.8	-0.4	4	6	1	0.7	-1.3	2.0	-0.4	1	9	1
- NW.I	1.3	-1.8	3.1	-0.2	4	7	0	1.3	-1.3	2.6	-0.2	3	7	1

Abbreviations:
(England) ANG – Anglian; HUM – Humber; NHM – Northumbria; NW.E – NW England; SE.E – SE England; SEV – Severn; SW.E – SW England; THA – Thames; **(Wales)** DEE – Dee; WW – W Wales; **(Scotland)** ARG – Argyll; CLY – Clyde; FOR – Forth; NE.S – NE Scotland; NH – N Highland; O&S – Orkney & Shetland; SOL – Solway; TAY – Tay; TW – Tweed; WH – W Highland; **(N. Ireland)** NB – Neagh Bann; NE.I – NE Ireland; NW.I – NW Ireland

Table 6.11: Cross correlation, across all WRRs, between the biases in the drought indices during the wet and dry seasons under extreme drought conditions for each ensemble member (afgcx to afixq). *DI* = drought intensity; *CI* = drought covariance index; *FDM* = frequency of drought months; *msRAIN* = mean seasonal rainfall; *msDSI6* = mean seasonal DSI6. Values with statistically significant correlation at the 90 % confidence level are underlined. Figures in parentheses show the climate sensitivity (K) of corresponding HadSM3 variant for each ensemble member. Subscripts d and w refer to the dry and wet seasons, respectively.

	CI_{d}	FDM_{d}	$msRAIN_{d}$	$msDSI6_{d}$	DI_{w}	CI_{w}	FDM_{w}	$msRAIN_{w}$	$msDSI6_{w}$
afgcx (3.53 K)									
DI_{d}	-0.47	0.61	-0.21	0.93	0.61	-0.11	-0.64	-0.56	0.81
CI_{d}		-0.52	0.23	-0.38	-0.08	0.31	0.51	0.41	-0.21
FDM_{d}			0	0.68	-0.13	-0.16	-0.98	-0.74	0.13
$msRAIN_{d}$				-0.17	-0.37	0.05	0.06	0.45	-0.17
$msDSI6_{d}$					0.52	-0.08	-0.69	-0.64	0.69
DI_{w}						0.14	0.08	-0.04	0.81
CI_{w}							0.09	0.14	0
FDM_{w}								0.80	-0.16
$msRAIN_{w}$									-0.2
afixa (2.58 K)									
DI_{d}	-0.44	0.63	-0.38	0.88	0.46	-0.27	-0.65	-0.50	0.35
CI_{d}		-0.33	0.48	-0.32	-0.02	0.61	0.32	0.35	-0.07
FDM_{d}			-0.33	0.58	-0.26	-0.3	-0.97	-0.70	-0.29
$msRAIN_{d}$				-0.38	0	0.26	0.35	0.66	0.14
$msDSI6_{d}$					0.43	-0.27	-0.62	-0.42	0.36
DI_{w}						-0.06	0.23	0.23	0.81
CI_{w}							0.34	0.32	-0.14
FDM_{w}								0.73	0.27
$msRAIN_{w}$									0.14
afixc (2.81 K)									
DI_{d}	-0.15	0.16	-0.07	0.89	0.85	0.11	-0.33	0.13	0.70
CI_{d}		-0.39	0.12	-0.17	0.07	0.63	0.40	-0.08	0.12
FDM_{d}			0.06	0.2	-0.13	-0.36	-0.89	-0.18	-0.34
$msRAIN_{d}$				0.01	0	-0.24	0.03	0.55	-0.02
$msDSI6_{d}$					0.75	-0.06	-0.36	0.09	0.62
DI_{w}						0.21	0.03	0.21	0.84
CI_{w}							0.40	-0.17	0.07
FDM_{w}								0.33	0.18
$msRAIN_{w}$									0.2
afixh (3.43 K)									
DI_{d}	-0.72	0.77	-0.2	0.92	0.86	-0.35	-0.78	-0.43	0.69
CI_{d}		-0.66	0.07	-0.77	-0.60	0.60	0.70	0.33	-0.56
FDM_{d}			-0.16	0.74	0.42	-0.34	-0.99	-0.62	0.24
$msRAIN_{d}$				-0.03	-0.1	-0.2	0.16	0.63	0.03
$msDSI6_{d}$					0.84	-0.46	-0.78	-0.34	0.77
DI_{w}						-0.25	-0.45	-0.13	0.89
CI_{w}							0.35	0.02	-0.38
FDM_{w}								0.65	-0.29
$msRAIN_{w}$									-0.01

afixi (4.39 K)

DI_d	-0.63	0.63	-0.1	0.91	0.53	-0.01	-0.62	-0.3	0.09
CI_d		-0.49	-0.12	-0.50	-0.15	0.52	0.49	0.3	0.14
FDM_d			-0.01	0.53	-0.16	-0.33	-0.99	-0.66	-0.59
$msRAIN_d$				0.01	-0.12	-0.16	0.06	0.33	-0.27
$msDSI6_d$					0.58	-0.02	-0.51	-0.24	0.13
DI_w						0.2	0.19	0.36	0.72
CI_w							0.35	0.29	0.33
FDM_w								0.71	0.60
$msRAIN_w$									0.62

afixj (3.89 K)

DI_d	-0.44	0.26	-0.11	0.94	0.49	-0.44	-0.37	-0.18	0.44
CI_d		-0.89	-0.40	-0.40	0.17	0.62	0.81	0.29	0.24
FDM_d			0.59	0.19	-0.42	-0.40	-0.91	-0.39	-0.46
$msRAIN_d$				-0.19	-0.29	-0.25	-0.50	-0.11	-0.44
$msDSI6_d$					0.50	-0.47	-0.29	-0.17	0.51
DI_w						-0.09	0.46	0.59	0.91
CI_w							0.36	0.11	-0.06
FDM_w								0.61	0.48
$msRAIN_w$									0.57

afixk (4.44 K)

DI_d	-0.03	0.42	-0.07	0.94	0.3	-0.47	-0.55	-0.44	0.24
CI_d		-0.58	-0.22	-0.03	0.53	0.57	0.55	0.14	0.47
FDM_d			0.55	0.43	-0.55	-0.72	-0.96	-0.47	-0.56
$msRAIN_d$				-0.09	-0.40	-0.14	-0.45	0.22	-0.39
$msDSI6_d$					0.36	-0.49	-0.52	-0.41	0.28
DI_w						0.29	0.51	0.23	0.79
CI_w							0.68	0.53	0.41
FDM_w								0.51	0.49
$msRAIN_w$									0.38

afixl (4.88 K)

DI_d	-0.43	0.17	0.17	0.93	0.78	-0.34	-0.13	0.24	0.73
CI_d		-0.64	0.01	-0.36	-0.06	0.58	0.58	0.3	-0.05
FDM_d			0.27	0.13	-0.39	-0.39	-0.98	-0.51	-0.38
$msRAIN_d$				0.11	0	-0.09	-0.21	0.13	-0.06
$msDSI6_d$					0.79	-0.43	-0.11	0.31	0.79
DI_w						-0.15	0.41	0.61	0.96
CI_w							0.3	0.01	-0.23
FDM_w								0.57	0.39
$msRAIN_w$									0.64

afixm (4.54 K)

DI_d	-0.53	0.46	-0.23	0.95	0.68	-0.21	-0.50	-0.11	0.50
CI_d		-0.50	0.29	-0.53	-0.36	0.63	0.52	0.28	-0.26
FDM_d			0.07	0.47	-0.21	-0.33	-0.99	-0.53	-0.33
$msRAIN_d$				-0.22	-0.47	0.02	-0.05	0.14	-0.44
$msDSI6_d$					0.66	-0.3	-0.50	-0.18	0.51
DI_w						-0.12	0.18	0.26	0.90
CI_w							0.33	0.2	-0.16
FDM_w								0.53	0.3
$msRAIN_w$									0.35

afixo (4.79 K)

DI_d	-0.82	0.86	-0.15	0.99	0.90	-0.44	-0.87	-0.39	0.75
CI_d		-0.82	0.09	-0.83	-0.75	0.46	0.77	0.36	-0.63
FDM_d			-0.21	0.84	0.61	-0.54	-0.97	-0.59	0.43
$msRAIN_d$				-0.14	-0.08	-0.12	0.3	0.61	0.05
$msDSI6_d$					0.91	-0.40	-0.84	-0.37	0.79
DI_w						-0.23	-0.63	-0.12	0.90
CI_w							0.56	0.35	-0.23
FDM_w								0.66	-0.47
$msRAIN_w$									0.06

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DI_d	-0.23	0.27	-0.21	0.86	0.2	0.07	-0.37	-0.24	0.23
CI_d		-0.79	-0.42	-0.12	0.67	0.33	0.80	0.53	0.71
FDM_d			0.45	0.26	-0.77	-0.2	-0.98	-0.72	-0.78
$msRAIN_d$				-0.21	-0.63	-0.44	-0.42	0.04	-0.57
$msDSI6_d$					0.24	-0.13	-0.32	-0.33	0.2
DI_w						0.25	0.75	0.58	0.96
CI_w							0.17	0.03	0.2
FDM_w								0.71	0.75
$msRAIN_w$									0.64

Table 6.12: Summary of bias magnitudes averaged over England (ENG), Wales (WAL), Scotland (SCO) and Northern Ireland (NI) for a) mean seasonal rainfall (*msRAIN*), b) mean seasonal DSI6 (*msDSI6*), c) drought intensity (*DI*), d) drought covariance index (*CI*) and e) frequency of drought months (*FDM*) during the wet and dry seasons under extreme and moderate drought conditions. f) and g) show the frequency of drought events at a given duration (*FDD*) for moderate and extreme droughts, respectively, with persistence of at least 3 (FDD_3), 6 (FDD_6), 10 (FDD_{10}) and 12 (FDD_{12}) months. Data show the ensemble maximum (Max), minimum (Min), and mean (Mean), and are expressed as percentage change relative to the observed data, except for f) and g) which show absolute change. The ensemble spread (Spr) is expressed as the difference between ensemble maximum and ensemble minimum.

	a) Mean seasonal rainfall (*msRAIN*)								b) Mean seasonal DSI6 (*msDSI6*)							
	Dry season				Wet season				Dry season				Wet season			
	Max	Min	Spr	Mean	Max	Min	Spr	Mean	Max	Min	Spr	Mean	Max	Min	Spr	Mean
ENG	18.1	-30.3	48.4	-4.9	17.6	-0.3	17.9	7.8	-1.4	-41.3	39.9	-25.7	90.8	1.7	89.1	46.1
WAL	17.1	-30.3	47.5	-5.2	14.2	-6.9	21.1	3.8	-16.2	-43.9	27.7	-30.4	83.1	5.5	77.6	43.4
SCO	12.4	-22.1	34.5	-3.3	0.3	-16.1	16.4	-7.9	5.6	-41.6	47.2	-21.2	52.0	-8.9	60.9	23.8
NI	4.6	-30.6	35.2	-9.9	-2.2	-14.1	11.9	-8.4	4.1	-46.7	50.7	-22.0	57.2	2.2	55.0	29.0

c) Drought intensity (*DI*)

	Moderate drought								Extreme drought							
	Dry season				Wet season				Dry season				Wet season			
	Max	Min	Spr	Mean	Max	Min	Spr	Mean	Max	Min	Spr	Mean	Max	Min	Spr	Mean
ENG	-3.7	-46.6	42.9	-26.2	220.6	48.5	172.2	123.8	13.1	-31.4	44.5	-15.2	43.5	-12.8	56.2	17.5
WAL	-5.8	-45.3	39.5	-27.0	163.4	37.7	125.7	96.2	-5.1	-35.8	30.6	-19.7	33.4	-12.9	46.3	13.3
SCO	10.8	-39.5	50.2	-19.7	92.8	6.6	86.1	49.1	20.6	-29.8	50.4	-8.6	33.2	-17.8	51.0	6.2
NI	3.8	-46.2	50.0	-22.1	103.1	6.8	96.3	51.9	11.7	-38.5	50.2	-11.1	34.2	-3.9	38.1	14.1

d) Drought covariance index (*CI*)

	Moderate drought								Extreme drought							
	Dry season				Wet season				Dry season				Wet season			
	Max	Min	Spr	Mean	Max	Min	Spr	Mean	Max	Min	Spr	Mean	Max	Min	Spr	Mean
ENG	30.2	-4.5	34.8	9.7	6.7	-5.7	12.4	0.4	71.7	-7.4	79.0	25.4	36.0	-8.6	44.6	14.3
WAL	11.8	-3.1	14.9	1.8	1.1	-3.7	4.8	-1.3	28.3	-4.9	33.1	8.7	16.5	-4.1	20.6	7.2
SCO	25.8	-1.9	27.6	10.6	6.9	-5.2	12.1	0.7	62.2	-5.5	67.7	25.0	30.8	-14.2	45.0	7.5
NI	19.8	-11.4	31.2	2.0	5.6	-9.0	14.6	-2.5	63.6	-12.1	75.7	15.5	33.2	-20.0	53.2	3.9

e) Frequency of drought months (*FDM*)

	Moderate drought								Extreme drought							
	Dry season				Wet season				Dry season				Wet season			
	Max	Min	Spr	Mean	Max	Min	Spr	Mean	Max	Min	Spr	Mean	Max	Min	Spr	Mean
ENG	-8.7	-43.2	34.5	-25.9	57.0	12.1	44.8	34.6	-1.2	-52.2	51.0	-24.1	57.0	2.6	54.4	27.4
WAL	-2.9	-21.3	18.3	-12.8	33.2	4.7	28.5	19.9	5.9	-19.9	25.8	-8.1	21.7	-6.3	28.0	8.9
SCO	-11.7	-42.5	30.8	-27.8	52.4	14.5	37.9	34.1	-6.3	-52.8	46.6	-27.4	58.0	8.3	49.7	30.8
NI	-5.8	-34.7	28.9	-20.4	45.0	8.4	36.6	26.5	-0.3	-45.7	45.4	-19.9	51.2	1.4	49.8	22.8

f) Frequency of drought events at a given duration (*FDD*): Moderate drought

	FDD_3				FDD_6				FDD_{10}				FDD_{12}			
	Max	Min	Spr	Mean	Max	Min	Spr	Mean	Max	Min	Spr	Mean	Max	Min	Spr	Mean
ENG	8.1	-1.7	9.8	2.5	3.6	-0.4	4.0	1.6	1.1	-4.4	5.5	-1.4	0.7	-3.4	4.1	-1.4
WAL	11.4	0.3	11.1	4.8	4.2	0.3	3.9	2.7	1.2	-4.6	5.8	-1.7	0.1	-3.7	3.8	-1.8
SCO	5.6	-4.2	9.8	-0.2	2.7	-0.8	3.5	1.0	2.5	-2.0	4.5	0.3	1.9	-1.7	3.6	0.1
NI	9.7	-3.9	13.6	0.2	2.8	-1.8	4.6	0.9	3.3	-4.0	7.3	0.9	2.5	-3.0	5.5	0.4

g) Frequency of drought events at a given duration (*FDD*): Extreme drought

	FDD_3				FDD_6				FDD_{10}				FDD_{12}			
	Max	Min	Spr	Mean	Max	Min	Spr	Mean	Max	Min	Spr	Mean	Max	Min	Spr	Mean
ENG	3.0	-0.9	3.9	1.0	0.7	-2.0	2.6	-0.5	0.3	-1.6	1.9	-0.6	0.5	-1.0	1.5	-0.3
WAL	4.5	-0.5	5.0	2.4	1.1	-2.3	3.3	-0.5	0.0	-2.7	2.7	-1.7	0.3	-1.4	1.7	-0.8
SCO	2.5	-0.6	3.1	0.9	1.5	-0.8	2.3	0.4	0.6	-1.3	1.9	-0.3	0.7	-1.1	1.7	-0.2
NI	3.3	-0.6	4.0	1.2	1.9	-1.3	3.2	0.8	1.0	-1.7	2.7	-0.3	0.9	-1.2	2.2	-0.3

Chapter 7

21st Century Drought Scenarios for the UK

Abstract

This chapter addresses the fourth objective of the thesis: "*To examine the changes in 21st century drought characteristics in the UK projected by the UKMO RCMs*" and is based on the following paper published in *Water Resources Management*:

Rahiz M and New M (2013) 21st century drought scenarios for the UK. *Water Resources Management*, 27: 1039-1061. DOI: 10.1007/s11269-012-0183-1.

The rationale of this chapter is to develop scenarios for the spatial and temporal behaviour of droughts in the UK under climate change. These scenarios can then be used to assess drought risk in the light of existing and projected demand for water and the possibility of changes in water availability during drought events.

A 6-month drought severity index (DSI6) is applied to each of the 11 members of the HadRM3-PPE-UK perturbed-physics ensemble from 1950 to 2100 to investigate projected 21st century droughts in the UK, relative to the recent past. Four main drought characteristics are investigated: drought intensity (*DI*), drought covariance index (*CI*), frequency of drought months (*FDM*) and frequency of drought events at a given duration (*FDD*). The characteristics are analysed for 30-year periods: 1970-1999 (1980s), 2010–2039 (2020s), 2040–2069 (2050s) and 2070–2099 (2080s) and described in terms of their seasonal behaviour, for

both moderate and extreme droughts. Projections of drought characteristics are expressed in the forms of ensemble-mean change relative to the 1980s, as well as model consensus, in order to show the degree of agreement across the ensemble members, and analysed over 23 water resource regions. Results of the study are listed as follows:

- Drought intensity (*DI*): Ensemble-mean change in *DI* shows an increase over England and Wales. Higher magnitude of increase is exhibited for the 2050s and 2080s, for moderate droughts and during the wet season. There is large uncertainty in projections over England during the dry season;

- Drought covariance index (*CI*): Ensemble-mean change in *CI* is greatest (higher increase, more widespread and high consensus) during the dry season with the 2050s and 2080s showing similar spatial characteristics. Comparison between drought severities show a higher increase but less widespread for extreme droughts. Results therefore suggest that, under these conditions, future droughts are more coherent with higher probability that the same drought events are experienced across most regions;

- Local drought covariance index (*LCI*): Results of *LCI* point to the projected increase in drought coherence and risk in areas within 100 km of respective grid locations. General increase in *LCI* over the three future periods, with higher magnitude shown for extreme droughts and for the 2050s and

2080s. Largest increase exhibited over Scotland across the same time period. Moderate droughts are characterized by larger extent of area with high consensus;

- Frequency of drought months (*FDM*): Results show a large increase (and more widespread, covering England and Wales) in ensemble-mean change in *FDM* during the wet season, with comparable spatial patterns between the 2050s and 2080s. Larger area of no consensus, primarily over England, is shown during the dry season;

- Frequency of droughts at a given duration (*FDD*): There is a higher increase in ensemble-mean change in *FDD* for droughts with persistence of at least 3 and 6 months with a more profound increase (and more widespread, covering England and Wales) shown for moderate droughts. Longer duration droughts with persistence of at least 10 and 12 months show widespread increases in *FDD* under extreme drought conditions; and

- Water resource regions (WRRs): Most WRRs show decreases in *FDM* and *FDD* for droughts with persistence of at least 10 and 12 months and increases in *CI*, *LCI* and *FDD* for droughts with persistence of at least 3 and, to an extent, 6 months. Exceptions also apply for England and Wales which show increases in *DI* under both drought severities.

The significance of results from this study is that they show the largest impacts are on dry season water availability, especially in parts of England. In terms of water resources management, this would mean that regions whose water resource systems are dependent on recharge during the wet season are likely to show more sensitivity, hence greater vulnerability to droughts.

7.1 Introduction

In the UK, historical records have shown that droughts are a common feature of its climate (Marsh *et al*., 2007). The impact of these droughts varies depending on how they are managed and drought management by the water sector has clearly improved over time. For example, the 2003 UK drought was well mitigated to the extent that the impacts were modest (Marsh, 2004), whereas considerable impact was exerted by the 1995 drought (Walker and Smithers, 1998). Understanding how drought events might change under climate change is important for long-term water resource planning and regulation (Wade *et al*., 2007), and has been the focus of a number of studies in the UK, several of which are discussed below.

There is some degree of consistency in projections of future drought characteristics in the UK (*e.g.*, Fowler and Kilsby, 2004; Vidal and Wade, 2009). Using data from HadCM2 global climate model (GCM), Fowler *et al*. (2003) showed an 18 % increase in the duration of droughts for the period 2021–2050 relative to the reference period of 1961–1990 for the Yorkshire region, corresponding to an absolute increase from 165 to 196 days; for the period 2051–2080 drought duration increased further to 222 days, a 34 % change relative to the same reference period. Similarly, Fowler and Kilsby (2004) reported increases in projected drought severity and frequency in most regions of the UK for the period 2070–2100 although the authors acknowledged the overestimation and underestimation of drought characteristics in different parts of the UK by the regional climate model (RCM) when compared against the observed dataset. Changes in drought frequency, severity and duration for the British Isles have also been analyzed by Blenkinsop and Fowler (2007b) using an ensemble of RCMs as part of the European PRUDENCE project. Results for 2071–2100 indicated an increase in short-term summer droughts, whereas longer-term droughts are projected to become shorter and less severe. The results were however inconclusive as the authors noted large variability in projections by the RCMs. In a similar multi-model ensemble experiment, but using GCMs, Vidal and Wade (2009) observed a slight increase in extreme drought frequency for south of England for the 2020s relative to the 1970s. Except for the southeast region, most of England showed a large decrease in drought frequency for the 2050s. The 2080s on the other hand exhibited a north–south divide with higher increase in drought frequency in England (in particular the southeast).

These studies lend an insight on the behaviour of future droughts from a range of climate model simulations, but it is difficult to attach high confidence to the results due to uncertainties arising from natural climate variability, imperfect representation of the climate system within models, and uncertainties in future emissions (Fowler and Kilsby, 2007; Jenkins *et al*., 2009; Burke *et al*., 2010). Nonetheless, compared with GCMs, RCMs provide better representation of sub-grid scale processes and topographic features which are vital in simulating regional climates (Kittel *et al*., 1998). Comparatively, many aspects of an RCM's projections (*e.g.*, precipitation and temperature fields) are realistic as have been proven in several studies (Rummukainen, 2010).

To address modelling-related uncertainties in climate projections, two mainstream approaches have emerged. The multi-model ensemble (MME) experiment compares the output of simulations from different climate models to examine "structural" errors across models. In contrast, perturbed-physics ensemble (PPE) experiment investigates parameter errors within a single model, and forms an important additional method for quantifying uncertainties in climate projections (Allen, 1999; Pittock *et al*., 2001; Jenkins *et al*., 2009). In a PPE experiment a climate model is perturbed by adjusting different values of, ideally all, uncertain parameters within estimated "reasonable" ranges. Each simulation gives a picture of the evolution of climate for the past and future periods hence giving users the range of possible climate outcomes to work with for impact assessment, planning and management (Collins, 2007; New *et al*., 2007).

In the context of UK droughts, the dataset from the 2009 UK Climate Projections (UKCP09) PPE experiment (HadRM3-PPE-UK) has been utilized by Burke and Brown (2010), Burke *et al*. (2010) and Prudhomme *et al*. (2011) to assess within-model uncertainty. The first two studies addressed changes in future droughts. The third which looked at changes in future mean-flows will not be discussed here. Burke and Brown (2010) used a monthly accumulated drought metric to study the characteristics of 21st century droughts in terms of their duration, area, severity and return period. Results were reported as inconclusive as individual ensemble members showed either an increase or a decrease in drought frequency over England and Wales for the period 2049–2099 in which the magnitude of change lies within ±20 % relative to the period 1951–2001. There was more consistency in projections over Scotland and Northern Ireland which showed decreases from the same present-day period. The authors also concluded that there was slight change for the future period in drought extent and duration.

Burke *et al*. (2010) applied non-stationary extreme value theory and used a 3-, 6-, 12- and 18-month cumulative drought index to study the return level of droughts. The authors showed that the projected change in return level at the 25-year return period is dependent on the ensemble member which showed either an increase or a decrease in droughts (with the magnitude of increase being greater than the decrease). Nonetheless, the distribution of UK-averaged change of the same variable showed a predominant increase in drought by 20 % relative to the 1961–1990 mean. Similar to Burke and Brown (2010), the authors concluded that there was a considerable spread of values across ensemble members in which the magnitude of change varies from small to significant.

7.2 Aims and rationale

The aim of this paper is to explore the uncertainties in projections of 21st century meteorological droughts in the UK through analysis of drought characteristics using dataset from the UKCP09 PPE experiment. The rationale of this study stems from the need to understand the spatial and temporal behaviour of future drought risk in the UK in light of demand for water (existing and potential future changes) and the possibility of changes in water availability during drought events. The understanding of drought risk in turn could provide valuable information for water resources planning and management in the UK.

This study builds on the previous work by Burke and Brown (2010) and Burke *et al*. (2010) on future droughts in the UK using the HadRM3-PPE-UK dataset, and similar work, with main differences of this study listed as follows:

- The study takes a frequentist approach to understanding future drought risk in the UK in contrast with the probabilistic study by Burke and Brown (2010) and Burke *et al*. (2010), and also adopts the use of consensus plots which in the authors' opinion conveys better the uncertainties in projections of drought characteristics;

- Several aspects of drought characteristics, notably spatial coherence and frequency of events at a given duration, have not previously been investigated. In addition, the application of the dataset from the PPE experiment presents the opportunity to revisit projections of future droughts characteristics (*e.g.*, intensity and frequency) and assess the consistency of results with existing studies;

- The analysis is performed at the model grid resolution, and over 23 water resource regions (Figure 7.1), in contrast with the nine regions used in

Burke and Brown (2010). This is more representative of water supply regions for the country and allows for better understanding of regional drought vulnerability which in turn could provide clues on how water resources can be managed; and

- Three future time slices of 30 years are adopted to examine the changes in drought characteristics: 2030s, 2050s and 2080s. They present opportunities for stakeholders to assess the state of droughts at any given period and devise the optimum management options in light of short, medium and long term scenarios.

7.3 Data and methods

7.3.1 Climate model data: HadRM3-PPE-UK

The monthly precipitation dataset from 11 perturbed-physics versions (henceforth HadRM3-PPE-UK) of the Met Office Hadley Centre's regional climate model (HadRM3), developed for UKCP09, is used. The HadRM3-PPE-UK experiment is designed to simulate the regional climate for the UK for the period 1950–2100 for historical and medium (SRES A1B) emissions scenarios. The dataset contains one unperturbed member and 10 members with different perturbations to the atmospheric parameterizations (Murphy *et al*., 2007). All ensemble members are driven by the same historical and SRES A1B emissions scenarios. The HadRM3-PPE-UK uses a rotated pole grid with a resolution of 25 km (Jones *et al*., 2004). For this study, the dataset has been regridded using bilinear interpolation to a standard longitude-latitude grid of 0.225° to maintain consistency with the authors' complementary research on historical droughts (Rahiz and New, 2012).

7.3.2 Drought severity index

The drought severity index (DSI) is utilized to illustrate the temporal variability of droughts in the UK. It is a rainfall-based drought index developed by Phillips and McGregor (1998) based on an *n* month precipitation accumulation concept (Bryant *et al.*, 1994) and termination rule (Mawdsley *et al.*, 1994). In the context of UK, the index has been used in several studies (*e.g.*, Phillips and McGregor, 1998; Fowler and Kilsby, 2002a, 2004; Blenkinsop and Fowler, 2007b; Rahiz and New, 2012).

The study adopts a 6-month DSI (DSI6) which can be thought as more of a measure of hydrological drought (Phillips and McGregor, 1998). The DSI6 is applied on a grid basis to the entire precipitation time series from 1950 to 2099 for each of the 11-member ensemble run. The calculation of DSI6 is given as follows (after Phillips and McGregor, 1998);

Consider the monthly rainfall anomaly (defined in the current study as the difference from the 1961–1990 monthly mean) in month t, denoted X. If X is negative (*i.e.*, below its mean level) and rainfall in the 6-month period, X_t, $X_{t\text{-}1}$, $X_{t\text{-}2}$, ..., $X_{t\text{-}5}$, is lower than its 6-monthly mean, then initiate a drought sequence in month t, assigning the DSI a positive value that is equal to the precipitation deficit in month t.

Now consider the month t + 1. Suppose the rainfall anomalies in months t

and t + 1 were $-X$ mm and $-Y$ mm, respectively, then the DSI6 for month t + 1 equals $X + Y$, if and only if the 6-monthly mean total for the months t - 4, t - 3, t - 2, t - 1, t and t + 1 has not been exceeded. If the rainfall anomaly is positive in month t+1, then a drought can continue, with DSI6 = X - Y, provided that the 6-monthly mean total has not been exceeded. All drought sequences are terminated immediately when this 6-monthly mean total has been exceeded and DSI6 is assigned a value of zero.

To allow for comparison between locations, the index is standardized by dividing the DSI6 values by the location's mean annual rainfall and then multiplying by 100. The final index value will thus express the accumulated precipitation deficit as percentage of the mean annual rainfall of the location.

7.3.3 Time slices

At each grid cell, the DSI6 time series are divided into four 30-year periods covering 1970– 1999, 2010–2039, 2040–2069 and 2070–2099 and named after their respective middle decade *i.e.*, 1980s, 2020s, 2050s and 2080s. The primary factor for using timeslices is to provide drought scenarios for the short (2030s), medium (2050s) and long (2080s) terms. This is particularly useful in that such information allows the assessment of drought conditions (and devise appropriate response options) at different periods.

7.3.4 Seasonal disaggregation

Drought characteristics are examined in terms of the dry and wet seasons corresponding to the months of April-September and October-March, respectively. The dry/wet classification reflects the UK's hydrological cycle (including groundwater recharge and extraction), ending in the period of lowest flows in September. For each grid point and time period, a composite seasonal DSI6 dataset is created by extracting the DSI6 values for April-September for the dry season and October-March for the wet season from each year. For example, composite dataset for the 1980s during the dry season would therefore comprise the DSI6 values for each month from April to September for the years between 1970 and 1999.

7.3.5 Drought characteristics

The projected changes in five drought characteristics are calculated, for two drought severity levels: "extreme" and "moderate", represented by the 90th and 70th percentiles of DSI6, respectively. The drought characteristics – drought intensity (*DI*), domain-wide drought co-variance index (*CI*), local drought covariance index (*LCI*), frequency of drought months (*FDM*) and frequency of drought events at a given duration (*FDD*) – are calculated for each RCM ensemble member, on a grid point-by-grid point basis; the indices are defined in sections 7.3.5.1 to 7.3.5.4. Then, the ensemble-mean for each grid point is derived as the arithmetic mean of the 11 individual members. Projected change in each drought characteristic for the 2020s, 2050s and 2080s is expressed as ensemble-mean change relative to the 1980s.

In addition to calculating the ensemble-mean for each drought characteristic, the degree of consensus in direction of change in the 2020s, 2050s and 2080s is also calculated:

- High consensus (C_h): at least nine of the 11 members agree on direction of change;
- Moderate consensus (C_m): between seven and eight members agree on the direction of change; and
- No consensus (C_n): six or fewer members agree on the direction of change.

7.3.5.1 Drought intensity (*DI*)

DI is calculated as the 90th and 70th percentile DSI6 exceedence values (for all months) in each of the two seasons.

7.3.5.2 Drought covariance (*CI*) and local drought covariance (*LCI*) indices

The measure of the degree of spatial coherence of droughts is calculated using a drought covariance index (*CI*) introduced by Rahiz and New (2012). This is calculated by firstly identifying at each grid cell the years in which droughts exceed the 90th (or 70th) percentile threshold of the seasonal DSI6 time series. Then, iterating through each grid cell over the UK, the proportion of other grid cells that also exhibit a 90th (or 70th) percentile drought in the relevant years is determined.

CI is then calculated as the average of all pairwise *CI*s for that grid point. This provides the mean state of drought covariance of that grid point relative to all other grid points in the domain.

Also calculated is the local covariance index, *LCI*, defined as the average *CI* within 100 km of each grid point. This allows the assessment of drought coherence at a smaller spatial scale; a high *LCI* indicates a spatially extensive drought risk whereas a low *LCI* suggests that the risk is contained over a smaller area.

7.3.5.3 Frequency of drought months (*FDM*)

The *FDM* for each period and season is defined as the number of drought months in a 30-year timeslice that exceeds the 90th (or 70th) percentile of the entire 1980s' DSI6 time series.

7.3.5.4 Frequency of events at a given duration (*FDD*)

Calculation of *FDD* uses the full DSI6 time series, without seasonal sub-setting as in the previous indices. *FDD* is defined as the sum of the frequency of drought events, exceeding the 90th (or 70th) percentile of the 1980s' DSI6 time series, with persistence of at least *k* months within each future period, where *k* is 3, 6, 10 and 12.

7.4 Results

7.4.1 Projections of drought intensity (*DI*)

7.4.1.1 Dry season

The ensemble-mean change in *DI* and inter-model consensus during the dry season for the 2020s, 2050s and 2080s is given in Figure 7.2a and Figure 7.2b for extreme and moderate droughts, respectively. There is a large decrease in *DI* over most of Scotland (and with high consensus across ensemble members), with the patterns of decrease similar across all future periods and drought severities, except for the 2020s and under moderate drought, which see a greater extent of area characterized by a large decrease in *DI*. In contrast, *DI* increases over Wales and southwest England, and to an extent, parts of the Scottish highlands; these regions generally do not show high consensus across ensemble members. Greater magnitude of increase (and more widespread) is projected for the 2050s and 2080s, and for moderate droughts, encompassing also southeast England. The extent of area showing no consensus varies across periods, but generally characterizes most of southeast England (2020s), Humber and Northumbria (2050s) and Anglian (2080s).

7.4.1.2 Wet season

Patterns of change for the wet season are shown in Figure 7.2c (extreme droughts) and Figure 7.2d (moderate droughts). The patterns for the 2050s and 2080s are similar, with increases in *DI* (and with high consensus) over Northern Ireland, Wales, most of England and parts of Scottish Highlands, and with greater magnitude of increase for moderate compared to extreme droughts. The 2020s, on the other hand, exhibit smaller increases over Wales and England, and with larger area having no consensus and significantly fewer grid points with high consensus. The extent of areas characterized by a decrease in *DI* is small with the highest decrease shown over coastal areas in Scotland.

7.4.2 Projections of drought covariance index (*CI*)

7.4.2.1 Dry season

Ensemble-mean change in *CI* for the dry season for extreme and moderate droughts (Figure 7.3a and Figure 7.3b, respectively) shows a widespread increase over most of the UK, suggesting that future droughts are spatially and temporally more coherent. The patterns of change for the 2050s and 2080s are largely similar between the two drought severities but with lower consensus and higher magnitude of increase (but less widespread) shown for extreme droughts, and high consensus, lower magnitude of increase (but more widespread) exhibited by moderate droughts. There is consistency in the spatial patterns over northwest England and Anglian across both drought severities in which the regions show larger increases in *CI* compared with the rest of the UK, pointing to the higher probability that these regions would experience the same drought events in the future. The extent of area showing no consensus is more apparent for the 2050s under extreme droughts. The patterns for 2020s are similar across the two drought severities in terms of higher increases shown over coastal regions in

Scotland and Anglian. Comparatively, extreme droughts show larger area of no consensus over England, whereas there are more grid points which exhibit high consensus for moderate droughts.

7.4.2.2 Wet season

Ensemble-mean change in *CI* is generally small for both extreme (Figure 7.3c) and moderate (Figure 7.3d) droughts for the 2050s and 2080s during the wet season. For both periods, the spatial patterns of *CI* are largely similar with differences seen between severity levels: there are more areas characterized by higher increases (and smaller number of high consensus grid points) over north highland, northwest and southeast England for extreme droughts; for moderate droughts the same regions show lower increases in *CI* but contain more grid points with high consensus. The 2020s on the other hand show change of ±5 % for both severity levels with a larger decrease (over Northern Ireland) and more areas showing no consensus areas associated with extreme droughts.

7.4.3 Projections of local drought covariance index (*LCI*)

Projections of ensemble-mean changes in *LCI* are given in Figure 7.4a to Figure 7.4d for both seasons and drought severities. The patterns are largely similar to that of *CI* with higher magnitude of increase shown for extreme droughts and during the dry season, suggesting increased drought risk in areas within 100 km of respective grid locations under these conditions in the future.

Comparatively, there is widespread high consensus over the entire UK for the 2050s and 2080s during the dry season under moderate drought (Figure 7.4b). In addition, several regions see increases in *LCI*: Severn/Humber (2080s during the dry season under extreme droughts), north highland and northeast Scotland (2050s and 2080s for moderate droughts during both seasons, and for 2080s under moderate droughts during the wet season), and Wales (2020s under moderate droughts during the dry season).

7.4.4 Projections of frequency of drought months (*FDM*)

7.4.4.1 Dry season

The projected ensemble-mean change in *FDM* during the dry season, as shown in Figure 7.5a and Figure 7.5b for extreme and moderate droughts, respectively, depicts a general decrease over most of Scotland, Northern Ireland, northwest England and Humber/Northumbria across the three future periods with larger magnitude of decrease observed for moderate droughts. Consensus is not generally high in these areas, however. Southern England and Wales exhibit increases in *FDM* which is more significant in terms of spatial extent and magnitude for the 2050s and 2080s and for moderate droughts. In addition, areas which show higher increases in *FDM*, such as Wales, southwest and southeast England, have high model consensus. Within England, however, there is a greater extent of area in which there is no consensus across models with the 2050s representing the period with the largest area with no consensus.

7.4.4.2 Wet season

Patterns of ensemble-mean change in *FDM* for the wet season are similar for extreme (Figure 7.5c) and moderate (Figure 7.5d) droughts with slight difference in intensity of change which is greater for moderate droughts. Decrease in *FDM* is shown over most of Scotland, but more extensively for the 2020s than 2050s or 2080s. Both drought severities exhibit largely high consensus increases in *FDM* over England, Wales and parts of the Scottish Highlands for the 2050s and 2080s. Areas with highest increase in *FDM* are generally consistent across the two periods and encompass Wales and southwest England (extreme droughts) and the Anglian region (moderate droughts). The spatial patterns of increase for the 2020s are similar to that of other periods, but with a lower magnitude of increase. In addition, the 2020s contain a larger area within England which shows no consensus across models.

7.4.5 Projections of frequency of drought events at a given duration (*FDD*)

7.4.5.1 Extreme droughts

Figure 7.6 shows the changes in *FDD* with persistence of at least 3, 6, 10 and 12 months for extreme droughts. Projections across the three future periods and at different persistence durations show only small changes in event frequency, within ±1 event per 30-year; those areas with increases in *FDD* generally have high consensus across ensemble members.

Areas which exhibit increases in *FDD* are found over most of England and Wales, especially for shorter drought durations (least 3 and 6 months), whereas increases in *FDD* for longer drought persistence durations (*i.e.*, at least 10 and 12 months) generally characterize Wales, Northern Ireland and most of the northern parts of the UK. Droughts of shorter persistence (*e.g.*, at least 3 months) show a greater increase in *FDD* for the 2050s and 2080s and are more widespread than in the 2020s, covering Wales, Severn, southwest and southeast England with high consensus found over Wales and southwest England. The extent of area showing no consensus varies but is prominently seen over Scotland and southeast England.

7.4.5.2 Moderate droughts

For moderate droughts (Figure 7.7), there is a large increase in *FDD* with persistence of at least 3 months over all of the southern UK in the 2050s and 2080s, with high consensus across models. An emerging signal of increased frequency over the same geographic areas can be seen in the 2020s, but with lower consensus. It is only in the coastal areas of Scotland that *FDD* with persistence of at least 3 months decreases. A similar but less intense pattern of change occurs for droughts with persistence of at least 6 months, while for longer events there is a reversal to small reductions in *FDD*.

7.4.6 Analysis of water resource regions (WRRs)

Changes in drought characteristics for the 23 UK WRRs (Figure 7.1) are listed in aggregate form for extreme and moderate droughts for the 2080s in Table 7.1 and Table 7.2, respectively. The WRRs are used by the Environment Agency (England and Wales), the Scottish Environment Protection Agency and Northern Ireland

Environment Agency for strategic planning and reporting to the European Commission for the Water Framework Directive (EU Directive 2000/60/EC). The 2080s are chosen to maximize the climate change signal relative to the present (similar, but less distinct patterns of change are observed for the 2020s and 2050s, and are provided in Table A-11 to Table A-14 in Appendix A). In general, the tables show a high degree of consistency in the sign of change for each WRR, drought characteristic and severity level.

DI in the WRRs generally decreases, with a larger change during the dry season. However, most WRRs in the south (*e.g.*, SE and SW England, Severn and Thames) show increases in *DI*, suggesting enhanced drought stress in these already-stressed areas.

The change in *CI* shows an increase in all WWRs for both the dry and wet seasons and for both moderate and extreme drought severities. Similarly, the magnitude of change is larger during the dry season.

Change in *LCI* mimics that of *CI* with an increase in all WRRs for all seasons and drought severities. Larger change magnitude is shown during the dry season and for extreme droughts.

Most WRRs experience decreases in *FDM* during the dry season under both extreme and moderate droughts. The wet season, on the other hand, sees an increase in *FDM* for extreme droughts. For the same season and under moderate drought, most regions observe decreases in *FDM* although the magnitude of change is marginally different from the dry season.

The change in *FDD* depicts a decrease over most regions at longer persistence durations (*i.e.*, 10 and 12 months) for both drought severities. Most regions exhibit increases in *FDD* for droughts with shorter persistence but the increase is readily seen for moderate droughts with persistence of at least 3 months.

The index-correlation between changes in each drought characteristic across all WRRs is given in Table 7.3 and Table 7.4 for extreme and moderate droughts, respectively. The patterns of correlation between the drought severities are similar, although the drought indices have higher correlation coefficient under extreme drought conditions. In general, there is good correlation between the changes in drought statistics across the WRRs, with high positive correlation shown between *DI* and *FDM* (for all conditions), and between *DI* and *FDD* for droughts with short persistence durations (during the wet season and for both severity levels). The correlation between *DI* and *CI*, and *LCI*, is negative for all seasons and drought severities. In addition, WRRs with largest increases in *DI* show smallest increases in *CI*. This can be explained by either very high *CI* (at least 0.8) for the historical period (1980s), hence leaving little opportunity for further increases in *CI* for future periods (as in the case of moderate droughts), or small increase (or no increase) in *CI* for future periods (as in the case of extreme droughts).

7.5 Discussion and conclusions

Although droughts are, by definition, relatively rare phenomena, they have been a recurring feature of the climate of the UK. Burke and Brown (2010) and Burke *et* *al*. (2010) made the assertion that suitable techniques, such as a probabilistic approach, are essential to characterize droughts. Their study concluded that although projections show an overall increase in drought occurrence, there was considerable spread across ensemble members. Adopting a frequentist method, this study has showed that while the spread of results is evident, there is also a considerable extent to which there is consistency across ensemble members which show agreement in the sign of change. Key results of this study from the ensemble-mean projections are summarized as follows:

- Drought intensity (*DI*): Ensemble-mean change shows an increase in *DI* over England and Wales. Higher magnitude of increase is exhibited for the 2050s and 2080s, for moderate droughts and during the wet season. There is large uncertainty in projections over England during the dry season;

- Drought covariance index (*CI*): Ensemble-mean change in *CI* is greatest (higher increase, more widespread and high consensus) during the dry season with the 2050s and 2080s showing similar spatial characteristics. Comparison between drought severities show a higher increase but less widespread for extreme droughts. Results therefore suggest that, under these conditions, future droughts are more coherent with higher probability that the same drought events are experienced across most regions;

- Local drought covariance index (*LCI*): Results of *LCI* point to the projected increase in drought coherence and risk in areas within 100 km of respective grid locations. General increase in *LCI* over the three future periods, with higher magnitude shown for extreme droughts and for the 2050s and 2080s. Largest increase exhibited over Scotland across the same time period. Moderate droughts are characterized by larger extent of area with high consensus;

- Frequency of drought months (*FDM*): Results show a large increase (and more widespread, covering England and Wales) in ensemble-mean change in *FDM* during the wet season, with comparable spatial patterns between the 2050s and 2080s. Larger area of no consensus, primarily over England, is shown during the dry season;

- Frequency of droughts at a given duration (*FDD*): There is a higher increase in ensemble-mean change in *FDD* for droughts with persistence of at least 3 and 6 months with a more profound increase (and more widespread, covering England and Wales) shown for moderate droughts. Longer duration droughts with persistence of at least 10 and 12 months show widespread increases in *FDD* under extreme drought conditions;

- Water resource regions (WRRs): Most WRRs show decreases in *FDM* and *FDD* for droughts with persistence of at least 10 and 12 months and increases in *CI*, *LCI* and *FDD* for droughts with persistence of at least 3 and, to an extent, 6 months. Exceptions also apply for England and Wales which show increases in *DI* under both drought severities; and

- Proportion of domain: There is negative relationship between the magnitude of ensemble-mean change of each drought characteristics and the proportion of the UK domain. Moderate consensus characterizes about 45 % of the domain whereas high and no consensus each form less than 30 % of the domain (data not shown but are given in Table A-15 to Table A-20 in Appendix A).

There is difficulty in trying to find a direct comparison between this study and others considering that there are more variables offered in this study (*e.g.*, different seasons and severity levels) which have not been addressed in others. Nonetheless, the general results from this study share similar conclusions as that from other studies.

In terms of drought intensity, this study reports an increase especially for the wet season. The conclusion is also reflected in an earlier study by Fowler and Kilsby (2004) who observed increases in drought severity and frequency for the period 2070–2100 although the authors did not investigate seasonal changes. The increase in drought intensity during the wet season is also consistent with the findings by Prudhomme *et al*. (2011) who looked at changes in mean flow for the 2050s for each of the 11 RCMs used in this study. The authors reported a general increase in mean flow across the UK in winter with England and Wales showing between −20 % and 40 % change, whereas a predominant decrease is shown in summer, highest over Wales, northern England and Scotland.

The projected increase in frequency of drought months is consistent with the results from Fowler and Kilsby (2004) and Vidal and Wade (2009), particularly in identifying central and southeast England as regions vulnerable to future drought risk.

Frequency of droughts at a given duration has not been studied elsewhere, hence results showing their future changes are new. Several studies have investigated the projected changes in the duration of droughts. For example, an increase in the drought duration has been reported by Fowler *et al*. (2003). Blenkinsop and Fowler (2007b) reported an increase in short term summer drought and a decrease in long term droughts. Burke *et al*. (2010), however, showed that the duration of future droughts is similar to those for the present-day. This study shows that future droughts can persist over various durations. However, longer duration droughts have been projected to decrease compared with shorter duration droughts which are projected to become more frequent. This could be attributed to the fact that droughts of longer persistence durations are rare in the historical period (1980s) and are difficult to detect given the relatively small sample size (11 models, 30 years of data).

The projected increases in drought covariance indices (*i.e.*, *CI* and *LCI*) suggest that future droughts are more coherent, with higher probability of the same drought events experienced across locations and over a larger area. Results in this study show greatest change in coherence during the dry season. This contrasts with the study by Rahiz and New (2012) which looked at the spatial coherence of droughts using observed dataset from 1914 to 2006 in which higher coherence during the wet season was observed. The bias in the HadRM3-PPE-UK dataset, which has shown to have a ±30 % bias in mean monthly precipitation across ensemble members (Burke *et al*., 2010), could be a possible explanation for the observed seasonal differences in several drought characteristics (except for *CI* and *LCI*) which see greater change (and more widespread) for the wet season. However, this could not be ascertained as Burke *et al*. (2010) did not study the seasonal bias in the dataset.

All drought characteristics show differences in results between extreme and moderate drought conditions in which the latter, in general, exhibits larger change and is more widespread. This could partly be because setting lower threshold (*i.e.*, 70th percentile) increases the sample size to include less rare events, hence increasing the detectability of droughts.

While this study has quantified uncertainties through the use of the HadRM3-PPE-UK dataset and conveying the results in terms of the number of models in agreement with the sign of change, more needs to be done to understand the nature of uncertainties, such as investigating the factors or mechanisms that drive those uncertainties and how they propagate through time. Past studies have attributed UK droughts to either the prevalence of dry winters (Marsh, 2004; Briffa *et al*., 2009), the dominance of a certain weather type (Phillips and McGregor, 1998; Fowler and Kilsby, 2002a), atmospheric circulation or other large scale processes *e.g.*, North Atlantic Oscillation (Phillips *et al*., 2003). Work therefore is required to understand how such processes are represented in the HadRM3-PPE-UK and how they would change in the future. To the authors' knowledge, such work has not been done.

History has shown that droughts in the UK can vary considerably both in space and time. While most droughts have strong regional focus, the spatial extent of others, such as the UK drought of 1976, affects not only the entire country but also the wider European context. The unpredictability of weather patterns and population growth in England of which more than half is projected to be in the south is likely to pose serious challenges to existing water supply and infrastructure (New *et al*., 2007). This study contributes to the growing literature on droughts in light of a warming climate. It is hoped that results from the study would shed some understanding on future drought risk for water resources planning and management in the UK.

Table 7.1: Regionally-averaged ensemble-mean change for the 2080s (relative to the 1980s) in drought intensity (*DI*), drought covariance index (*CI*), local drought covariance index (*LCI*), frequency of drought months (*FDM*) and frequency of drought events (*FDD*) with persistence of at least 3, 6, 10 and 12 months under extreme droughts ($_{90}$) for 23 river basin regions. O&S refers to Orkney and Shetland; cardinal directions are abbreviated. Percentage change is shown for *DI* and *CI*, whereas absolute change (number of drought months and events per 30-year, respectively) is given for *FDM* and *FDD*. "-" denotes either no change or no data available.

	DI_{90}		CI_{90}		LCI_{90}		FDM_{90}		FDD_{90}			
	dry	wet	dry	wet	dry	wet	dry	wet	≥3	≥6	≥10	≥12
England												
- Anglian	-2.3	10.5	19.2	8.3	12.2	6.6	-1.0	11.7	1.2	0.3	-	-
- Humber	0.3	9.6	11.9	6.2	15.4	9.4	0.5	10.2	0.9	0.4	-	0.1
- Northumbria	-16.1	-4.3	19.7	12.4	12.7	10.4	-5.5	2.6	-0.3	-0.6	-0.1	-0.1
- NW England	-9.3	1.8	26.1	16.8	14.5	10.4	-2.7	4.8	0.4	0.1	-0.1	-0.1
- SE England	6.2	13.1	21.7	13.9	10.0	6.9	0.5	13.5	1.3	0.3	-0.1	-
- Severn	12.8	12.6	13.0	8.7	15.5	11.8	3.4	13.1	1.8	0.5	-	0.1
- SW England	15.0	13.0	16.0	15.9	12.0	10.5	3.5	14.8	1.9	0.2	-0.1	-
- Thames	6.0	15.5	11.8	10.8	10.7	9.2	0.4	14.7	1.6	0.4	-	-0.1
Scotland												
- Argyll	-25.9	-27.6	32.4	21.8	18.3	9.8	-7.6	-8.3	-1.1	-0.9	-0.2	-0.1
- Clyde	-23.6	-14.0	31.0	16.4	14.3	10.7	-6.4	-4.0	-0.5	-0.6	-0.1	-0.1
- Forth	-22.3	-10.4	25.7	14.3	16.7	12.7	-6.4	-1.5	-0.7	-0.7	-0.2	-0.1
- NE Scotland	-4.3	8.3	6.0	0.3	22.3	10.4	-0.6	5.3	0.7	0.5	0.1	-
- N Highland	-15.7	-3.6	27.1	15.5	24.6	12.6	-3.2	2.1	-0.1	0.1	-	0.1
- O&S	12.1	1.0	14.9	18.6	36.9	18.6	8.4	-0.9	0.8	0.9	0.5	0.3
- Solway	-18.0	-9.3	24.6	19.1	13.3	9.7	-4.5	0.2	-0.2	-0.2	-0.2	-0.1
- Tay	-6.0	0.9	18.4	8.6	16.2	10.4	-0.4	2.6	0.1	-0.2	-	-
- Tweed	-18.9	-5.9	17.7	14.4	17.7	10.0	-3.9	0.7	-0.2	-0.4	-0.1	-0.1
- W Highland	-25.3	-23.5	33.0	25.9	25.1	16.6	-8.9	-6.7	-1.3	-1.0	-0.3	-0.1
Northern Ireland												
- Neagh Bann	-13.3	-3.1	19.4	8.6	19.9	16.3	-3.9	0.6	0.1	0.1	-0.1	0.1
- NE Ireland	-14.1	-2.4	19.8	10.0	22.3	17.6	-3.8	1.5	0.1	0.2	-0.1	-0.1
- NW Ireland	-16.3	-3.3	26.8	8.4	14.9	11.9	-4.5	0.3	-0.1	-0.2	-	-

Wales												
- Dee	25.5	23.7	5.8	1.8	16.3	10.2	7.2	18.4	2.6	1.3	0.2	0.3
- W Wales	7.2	12.2	15.8	13.2	12.0	12.7	2.8	9.9	1.1	0.5	-	-

Table 7.2: As Table 7.1, but for moderate ($_{70}$) droughts.

	DI_{70}		CI_{70}		LCI_{70}		FDM_{70}		FDD_{70}			
	dry	wet	dry	wet	Dry	wet	dry	wet	≥3	≥6	≥10	≥12
England												
- Anglian	12.3	36.3	11.3	4.3	7.3	2.8	3.2	16.5	3.2	0.8	-0.3	-0.2
- Humber	3.7	30.4	8.1	4.3	8.2	3.1	3.7	13.9	3.3	0.8	-0.2	0.0
- Northumbria	-17.7	7.4	8.7	4.8	10.6	5.7	-6.2	6.9	2.3	0.2	-0.8	-0.4
- NW England	-7.9	6.8	12.9	6.5	10.3	3.1	-1.0	3.3	2.6	-0.5	-0.6	-0.5
- SE England	21.1	24.2	9.8	6.4	8.5	4.5	7.7	10.2	4.6	0.6	-0.3	-0.2
- Severn	27.6	24.7	8.8	4.6	9.2	3.6	8.2	12.9	4.6	1.0	-0.1	-0.1
- SW England	26.9	23.4	8.4	5.4	8.3	3.0	9.1	12.1	5.3	1.1	-0.3	-0.2
- Thames	30.6	32.8	10.4	5.2	8.4	3.7	7.7	16.0	4.7	1.0	-0.1	-0.1
Scotland												
- Argyll	-36.1	-50.5	19.8	9.9	12.6	5.1	-18.0	-20.1	-2.4	-1.8	-1.1	-0.7
- Clyde	-20.7	-16.4	18.6	9.2	9.0	2.5	-9.4	-10.3	-0.5	-1.3	-1.3	-1.0
- Forth	-29.6	-15.4	12.3	5.7	10.8	3.8	-12.4	-6.6	0.7	-1.0	-0.9	-0.7
- NE Scotland	-9.8	-2.6	5.5	-1.1	13.7	7.0	-5.0	2.3	1.0	0.3	0.2	0.1
- N Highland	-21.3	-17.4	10.5	3.0	13.6	7.2	-7.0	-4.0	0.8	-0.1	-0.2	-0.1
- O&S	7.0	-27.7	0.0	7.3	18.4	8.1	2.6	-11.9	0.0	0.1	-0.1	0.4
- Solway	-14.8	-9.1	15.9	6.9	10.2	3.9	-5.2	-3.3	1.5	-0.9	-1.1	-0.6
- Tay	-6.5	-3.2	11.9	4.0	11.0	4.7	-2.8	-1.2	1.2	-0.4	-0.4	-0.1
- Tweed	-23.0	-4.2	9.9	4.4	10.0	3.8	-9.0	0.6	1.7	0.1	-0.8	-0.4
- W Highland	-32.8	-44.8	19.1	8.8	14.1	6.3	-18.8	-17.8	-2.2	-1.7	-1.2	-0.8
Northern Ireland												
- Neagh Bann	-20.8	-3.0	10.3	5.8	10.9	4.8	-7.9	-0.7	0.4	-0.9	-0.8	-0.1
- NE Ireland	-20.8	-6.9	13.9	5.1	11.7	4.6	-8.9	4.4	0.4	-0.9	-0.9	0.0
- NW Ireland	-14.2	-6.5	9.4	6.6	9.9	3.6	-5.3	-4.8	0.9	-0.8	-0.9	-0.2
Wales												
- Dee	42.5	33.0	8.3	3.0	10.6	4.1	12.4	17.6	5.0	1.5	0.3	0.4
- W Wales	10.4	16.7	10.7	4.9	10.4	3.9	6.4	7.5	3.8	-0.2	-0.2	-0.2

Table 7.3: Index-correlation across all water resource regions for extreme ($_{90}$) droughts

	DI_{90}		CI_{90}		LCI_{90}		FDM_{90}		FDD_{90}			
	dry	wet	dry	wet	dry	wet	Dry	wet	≥3	≥6	≥10	≥12
DI_{90}												
dry	1.00											
wet	0.90	1.00										
CI_{90}												
dry	-0.78	-0.83	1.00									
wet	-0.46	-0.69	0.76	1.00								
LCI_{90}												
dry	-0.10	-0.32	0.04	0.21	1.00							
wet	-0.14	-0.32	0.13	0.25	0.77	1.00						
FDM_{90}												
dry	0.96	0.82	-0.77	-0.42	0.10	-0.02	1.00					
wet	0.86	0.96	-0.73	-0.58	-0.48	-0.46	0.72	1.00				
FDD_{90}												
≥3	0.96	0.96	-0.79	-0.57	-0.28	-0.29	0.88	0.95	1.00			
≥6	0.88	0.87	-0.81	-0.60	0.09	-0.01	0.91	0.75	0.88	1.00		
≥10	0.70	0.54	-0.68	-0.39	0.59	0.26	0.85	0.32	0.58	0.80	1.00	
≥12	0.77	0.57	-0.61	-0.46	0.49	0.28	0.84	0.45	0.65	0.80	0.87	1.00

Table 7.4: As Table 7.3, but for moderate ($_{70}$) droughts.

	DI_{70}		CI_{70}		LCI_{70}		FDM_{70}		FDD_{70}			
	dry	wet	dry	wet	dry	wet	dry	wet	≥3	≥6	≥10	≥12
DI_{90}												
dry	1.00											
wet	0.82	1.00										
CI_{90}												
dry	-0.52	-0.43	1.00									
wet	-0.33	-0.50	0.58	1.00								
LCI_{90}												
dry	-0.37	-0.71	-0.20	0.05	1.00							
wet	-0.27	-0.53	-0.32	-0.17	0.89	1.00						
FDM_{90}												
dry	0.97	0.86	-0.60	-0.38	-0.39	-0.29	1.00					
wet	0.79	0.98	-0.44	-0.58	-0.64	-0.45	0.83	1.00				
FDD_{90}												
≥3	0.88	0.94	-0.47	-0.45	-0.62	-0.45	0.92	0.93	1.00			
≥6	0.87	0.85	-0.69	-0.61	-0.36	-0.15	0.88	0.87	0.88	1.00		
≥10	0.78	0.63	-0.75	-0.72	0.01	0.17	0.79	0.66	0.67	0.84	1.00	
≥12	0.61	0.46	-0.82	-0.62	0.21	0.32	0.64	0.52	0.45	0.67	0.83	1.00

Figure 7.1: Map of the 23 water resource regions (WRRs) used in this study. Source: Jenkins *et al.* (2009)

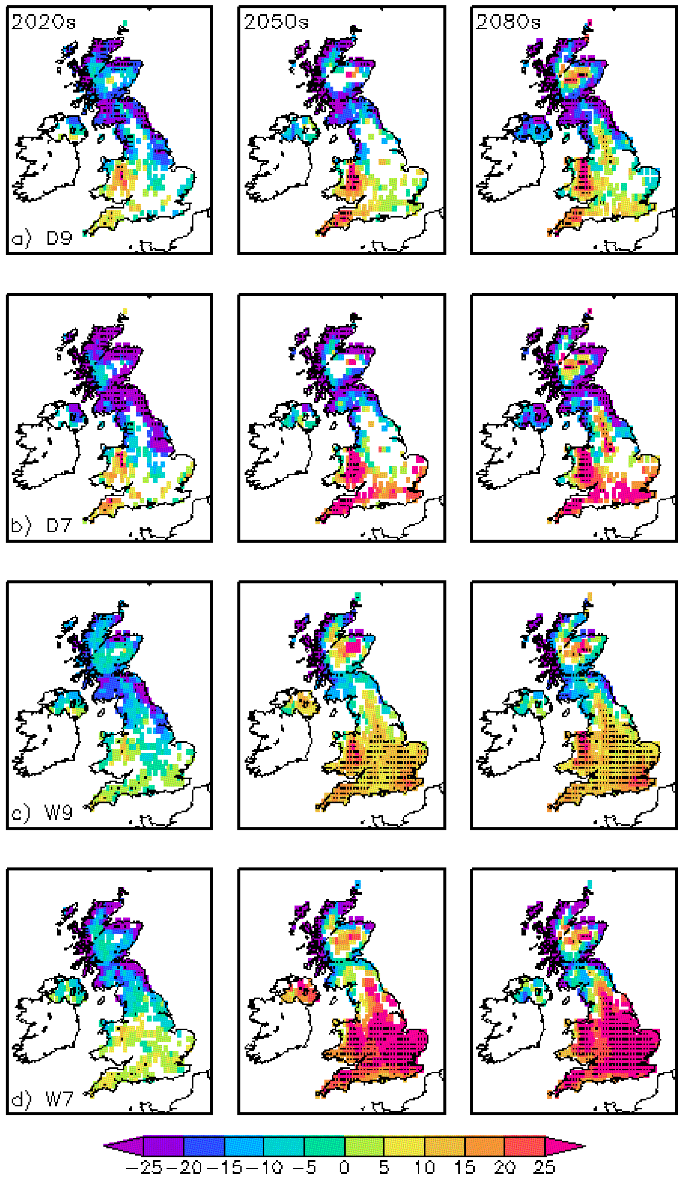

Figure 7.2: Ensemble-mean change and consensus of change in drought intensity (*DI*) for the 2020s, 2050s and 2080s for the wet (W) and dry (D) seasons for extreme (9) and moderate (7) droughts (*e.g.*, a "D7" refers to the dry season's moderate drought). Colour bar shows percentage change relative to the 1980s. Coloured grids show at least seven models which agree with the sign of change; black stippling shows at least nine models in agreement with the sign of change; masked areas (*i.e.*, white) show where six (or fewer) models agree on the sign of change.

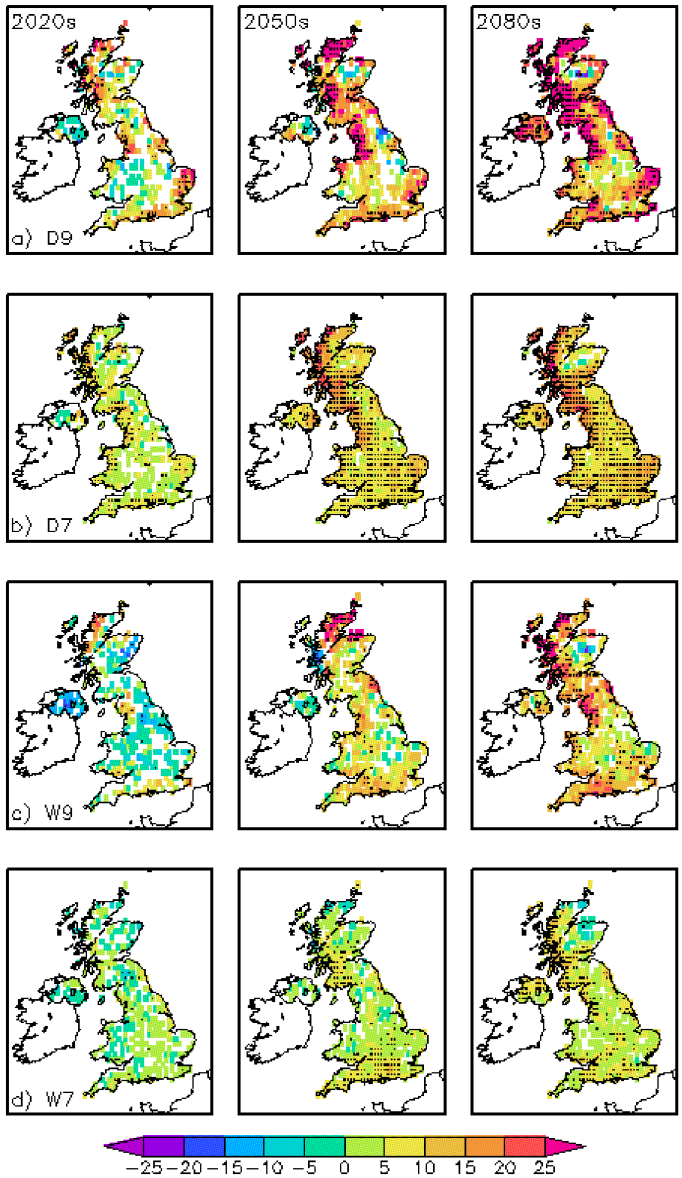

Figure 7.3: As Figure 7.2, but for drought covariance index (*CI*).

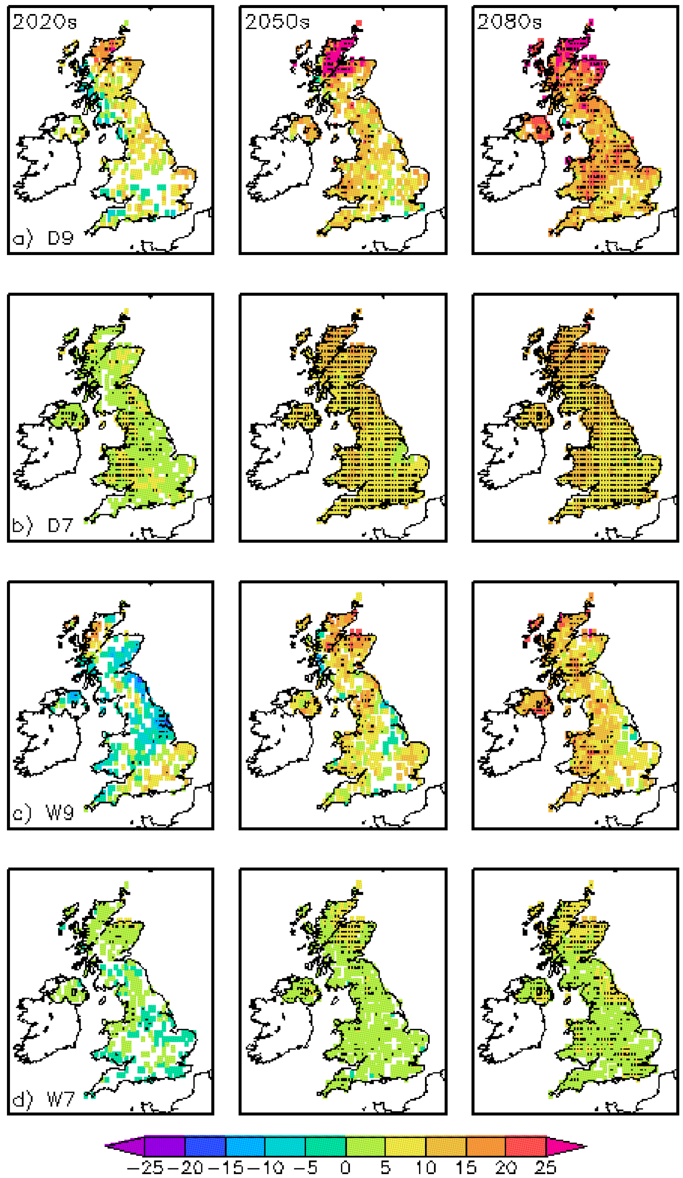

Figure 7.4: As Figure 7.2, but for local drought covariance index (*LCI*).

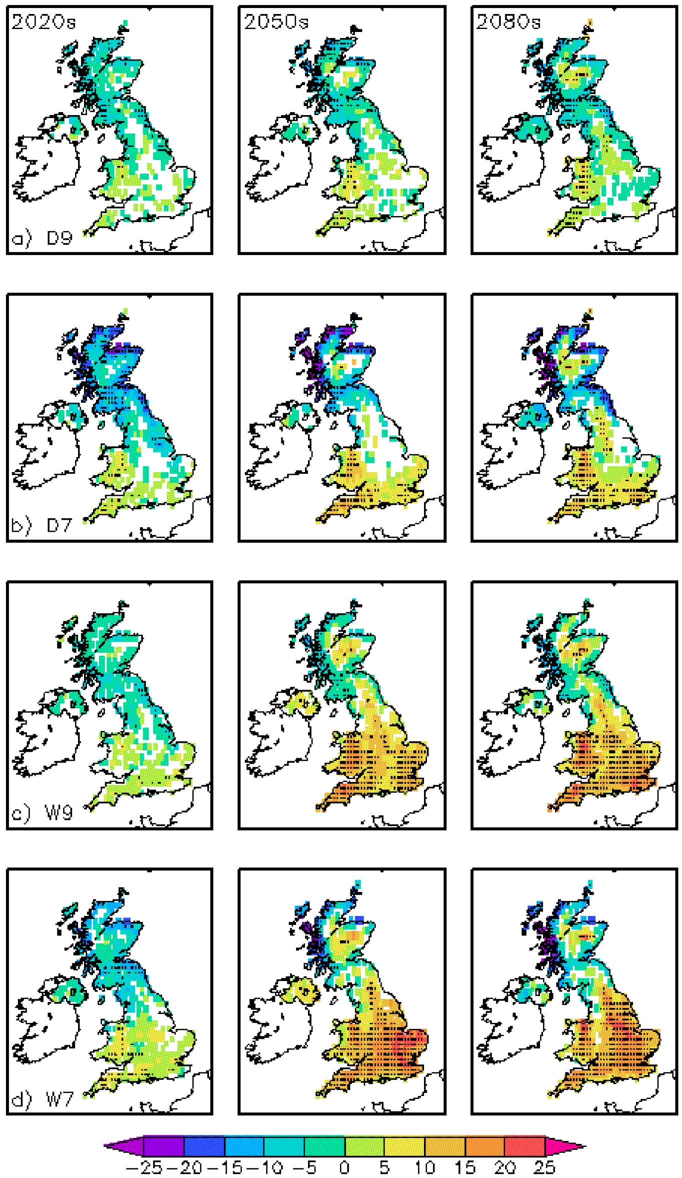

Figure 7.5: As Figure 7.2, but for frequency of drought months (*FDM*). Colour bar shows absolute change (expressed as number of drought months per 30-year) relative to the 1980s.

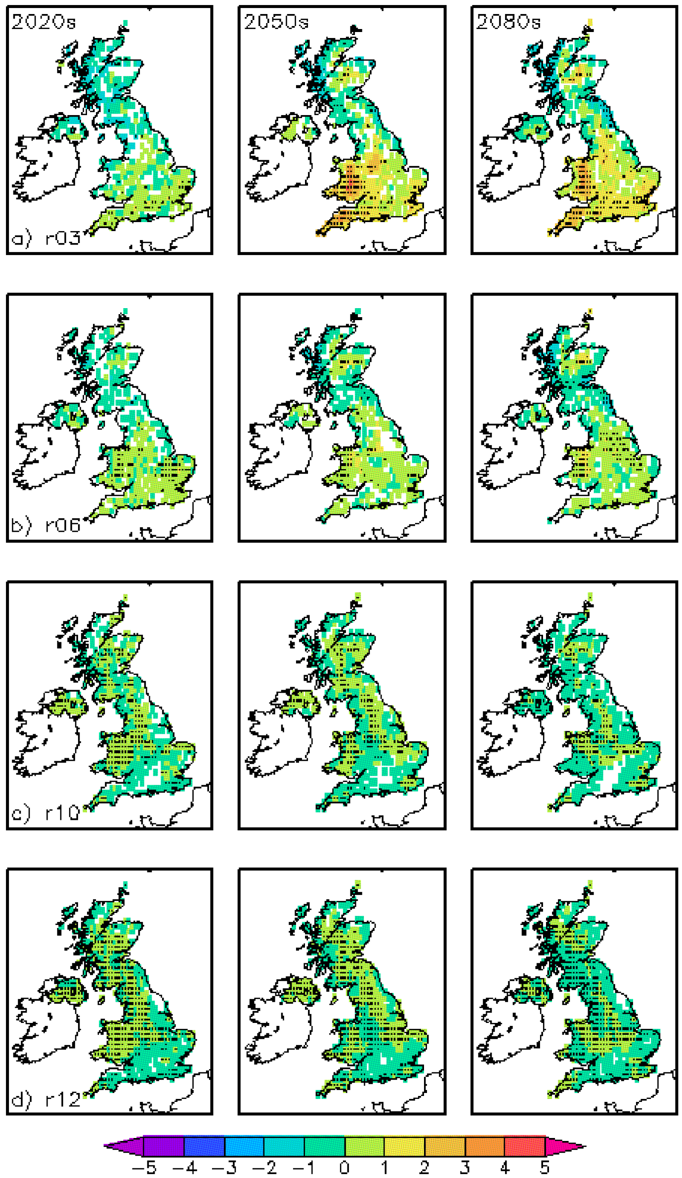

Figure 7.6: Ensemble-mean change in frequency of drought events (*FDD*) with persistence of at least (a) 3 (r03), (b) 6 (r06), (c) 10 (r10) and (d) 12 (r12) months for extreme droughts for the 2020s, 2050s and 2080s. Colour bar shows the absolute change (expressed as number of events per 30-year) relative to the 1980s. Coloured grids show at least seven models which agree with the sign of change; black stippling shows at least nine models in agreement with the sign of change; areas with six (or fewer) models which agree with the sign of change are masked (*i.e.*, white).

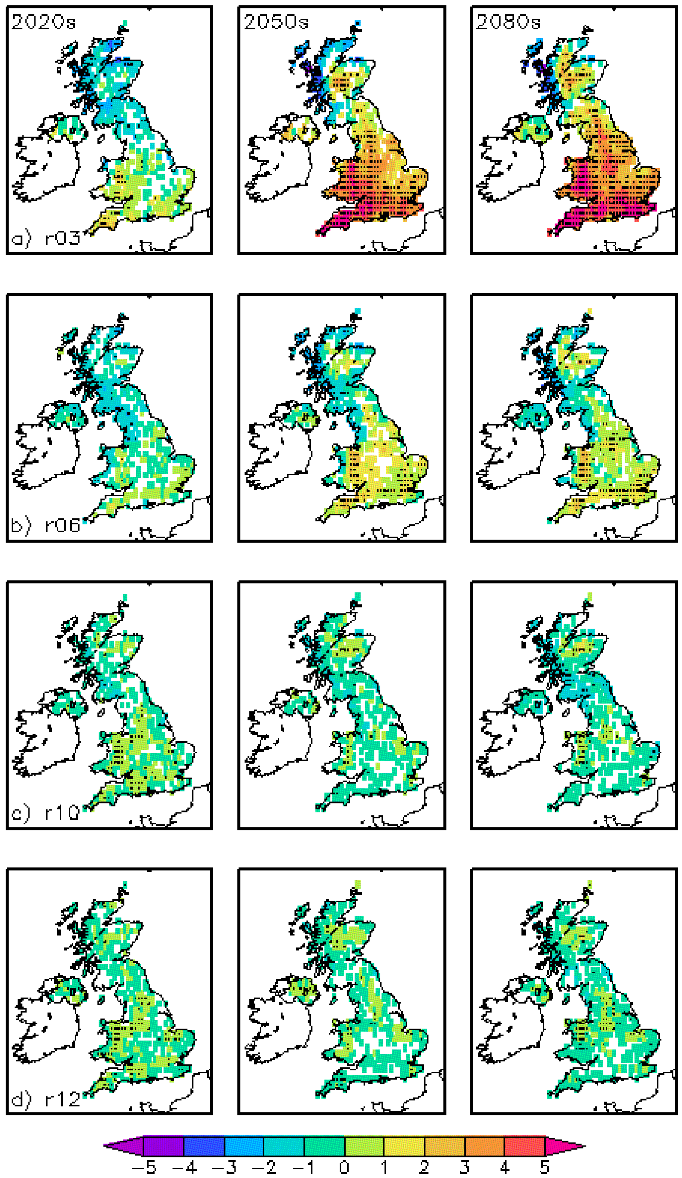

Figure 7.7: As Figure 7.6, but for moderate droughts.

Chapter 8

Conclusions and Outlook

This thesis presents a compilation of four research papers which seek to investigate the changes in the characteristics of 20th and 21st century meteorological droughts in the UK. Each of the papers address a specific objective as listed in Chapter 1.1. A rainfall-based drought index, the drought severity index (DSI), is used as the core index for drought detection. The DSI is applied at different time scales (*i.e.*, 3-, 6-, 10-, 12- and 24-month) to monthly precipitation from observed and 11-member regional climate model datasets to analyze four drought characteristics – drought intensity (*DI*), drought covariance index (*CI*), frequency of drought months (*FDM*) and frequency of drought events at a given duration (*FDD*) – under extreme and moderate drought severity conditions, and during the dry and wet seasons.

In this concluding chapter, four parts are presented. First, a summary of the main findings of the four research papers as reported in Chapters 4-7 is given. Second, a discussion is given on the implications of the study for water resources management in the UK. Third, some recommendations from which further work can be initiated are provided. The chapter ends with some concluding remarks.

8.1 Summary of thesis

8.1.1 Objectives and methodology

The first objective of the thesis – "*To assess the suitability of a rainfall-based drought index in representing hydrological droughts*" – is addressed in Chapter 4, "*Does a rainfall-based drought index simulate hydrological droughts?*". This chapter forms an important first step in the thesis as results determine the reliability of the index in not only detecting past and future droughts in the UK, but also its suitability for providing information in the context of water resources management and planning. In this paper, the DSI is applied at 3-, 6-, 12- and 24-month time scales to both monthly gridded rainfall and monthly river flow datasets. The time series of the flow- and rainfall-based DSIs are extracted from seven benchmark catchments in England to illustrate the study. These are then analyzed under different seasons (dry and wet) and severity (extreme and moderate) conditions, including the ability of the indices to reproduce the statistics of three drought characteristics: drought intensity (*DI*), frequency of drought months (*FDM*) and frequency of drought events at a given duration (*FDD*).

The second objective of the thesis – "*To examine the spatial coherence of droughts from the recent pas*t" – is addressed in Chapter 5, "*Spatial coherence of meteorological droughts in the UK since 1914*". The rationale of this paper is to understand the historical climatology of drought coherence so that better assessment of regional risk can be made in light of future climate change. The DSI is applied on a

3-, 6-, 12- and 15-month time scales to the UKMO monthly gridded precipitation dataset from 1914 to 2006. Analyses are undertaken for the wet and dry seasons, and under moderate and extreme drought severity conditions. To quantify the spatial coherence of droughts, a drought covariance index is introduced. This is calculated by first identifying the years with moderate (or extreme) droughts that exceeds the 70th (or 90th) percentile threshold of the entire seasonal DSI time series. Next, the fraction of years, *f*, with moderate (or extreme) droughts that each pair of grid points has in common is determined. Finally, for each grid point, the covariance index is calculated as the average of all pairwise *f* values for that grid point. This provides the average state of drought covariance of any given grid point relative to all other grid points in the UK.

Chapter 6, "*Evaluation of HadRM3-PPE-UK: Drought characteristics*" addresses the third objective of the thesis: "*To assess the reliability of the UKMO perturbed physics RCMs, used in the recent UKCP09, in the representation of drought characteristics*". The purpose of this paper is to establish confidence associated with using the model data, which underpin the UKCP09, in the projections of 21st century droughts in the UK (Chapter 7) and to understand the nature of limitations/uncertainties in the models (*e.g.*, estimation of magnitude of bias and their spatial patterns). A 6-month DSI (DSI6) is applied to each of the 11-member HadRM3-PPE-UK to evaluate their ability to simulate four observed drought characteristics: drought intensity (*DI*), drought covariance index (*CI*), frequency of drought months (*FDM*) and frequency of drought events at a given duration (*FDD*) under different drought severity (moderate and extreme) and seasonal (dry and wet) conditions. The HadRM3-PPE-UK is also evaluated in terms of the members' ability to reproduce the mean seasonal rainfall and mean seasonal DSI6, and their leading principle components.

Chapter 7, "*21st century drought scenarios for the UK*", forms the concluding research paper and addresses the final objective of the thesis: "*To examine the changes in 21st century drought characteristics in the UK projected by the UKMO RCMs*". The rationale of this chapter is to develop scenarios for the spatial and temporal behavior of droughts in the UK under future climate change. These scenarios can then be used to assess drought risk in the light of existing and projected demand for water and the possibility of changes in water availability during drought events. The paper applies a 6-month DSI (DSI6) to the same 11-member HadRM3-PPE-UK used in Chapter 6 for the period 1950-2100. The same drought characteristics, as used in preceding chapters, are investigated: drought intensity (*DI*), frequency of drought months (*FDM*) and frequency of drought events at a given duration (*FDD*). Changes in these characteristics for three 30-year future periods – 2020s (2010-2039), 2050s (2040-2069) and 2080s (2070-2099) – are expressed as ensemble-mean change relative to the period of the recent past, 1980s (1970-1999) and described in terms of their seasonal (wet and dry) behaviour under both extreme and moderate drought severity conditions, and over 23 water resource regions.

8.1.2 Key results

Key results that emerge from the objectives of the thesis are summarized as follows;

- Objective 1: *To assess the suitability of a rainfall-based drought index in representing hydrological droughts.* Key results:

    - There is very high (*rho* >0.9) and statistically significant correlation between the monthly gridded rainfall (MGR) and catchment monthly rainfall (CMR). This shows that MGR is a good proxy for catchment rainfall and can therefore be considered a reliable dataset from which climate change experiments can be evaluated against;

    - The rainfall-based drought index, the drought severity index (DSI), is able to capture periods of low flows. This is evident in the ability of the rainfall-based DSI ($MGR_{DSI\text{-}n}$) to capture major hydrological drought events as simulated by the flow-based DSI ($MRF_{DSI\text{-}n}$);

    - Generally, $MGR_{DSI\text{-}n}$ is able to represent moderate hydrological droughts better than extremes. This is shown by the smaller difference between $MGR_{DSI\text{-}n}$ and $MRF_{DSI\text{-}n}$ based on the statistics from the three drought characteristics *i.e.*, *DI*, *FDM* and *FDD*;

- There is a positive relationship between the time scale of DSI and the intensity (and duration) of the drought event it produces. A shorter DSI time scale (*e.g*., 3-month DSI) produces droughts which are less intense (and shorter in duration), whereas more intense (and longer duration) droughts are produced by a longer DSI time scale (*e.g.*, 12-month); and

- The main caveat of this study stems from the overestimation of drought intensity, caused by catchment-controlled processes, by $MRF_{DSI\text{-}n}$. This in turn generates droughts which are longer in duration.

- Objective 2: *To examine the spatial coherence of droughts from the recent past*. Key results:

  - Drought covariance is higher (*CI* ≥0.7) for the (i) wet season, (ii) moderate and (iii) shorter duration (*e.g*., DSI3 and DSI6) droughts compared with the dry season, extreme and longer duration (*e.g*., DSI12 and DSI24) droughts, respectively, which showed lower covariance (*CI* <0.6);

  - Spatially, highest drought covariance (*CI* ≥0.8) is shown for the north and west of the UK during the wet season under moderate drought conditions.

The pattern is most prominent and widespread short drought droughts (*i.e*., DSI3). For the same season but under extreme drought conditions, drought covariance is higher (*CI* between 0.5 and 0.7) in England and lowest (*CI* <0.2) in west Highlands; and

- The spatial patterns of spatial coherence decay during the dry season are largely similar between DSI6 and DSI15 under both moderate and extreme drought conditions. The main difference is that there is a greater proportion of the UK which is characterized by a larger percentage area within 100 km, 200 km, 300 km and 400 km of respective grids that is represented by high covariance (*CI* ≥0.8) for DSI6 and moderate droughts compared with DSI15 and for extreme droughts, respectively;

- During the dry season, a larger percentage of area within a given distance of respective grids which is represented by (*CI* ≥0.8) characterizes most regions in England, especially the southeast. This is most significant for DSI6 and DSI15 under moderate drought conditions in which at least 50 % of the area within 100 km of respective grids is represented by high covariance (*CI* ≥0.8); and

- During the wet season, virtually all of the UK has at least 50 % of the area within 100 km and 200 km of respective grids which is characterized by high covariance (*CI* ≥0.8) for DSI6. Increasing distance (*i.e.*, 300 km and 400 km), longer drought duration (*i.e.*, DSI15) and heightened severity (*i.e.*, extreme droughts) reduce not only the percentage of area with high covariance, but also the proportion of the UK it represents.

- Objective 3: *To assess the reliability of the UKMO perturbed physics RCMs, used in the recent UKCP09, in the representation of drought characteristics*. Key results:

  - Mean seasonal rainfall (*msRAIN*): Ensemble mean shows negative bias (within 9 %) across the domain for $msRAIN_d$, whereas $msRAIN_w$ shows positive biases over England (7 %) and Wales (3 %) but negative biases over Scotland (-7 %) and Northern Ireland (-8 %). Ensemble spread is larger for the $msRAIN_d$ than for $msRAIN_w$;

  - Mean seasonal DSI6 (*msDSI6*): Ensemble mean shows negative (within 40 %) and positive (>30 %) biases across most regions for $msDSI6_d$ and $msDSI6_w$, respectively. Both seasons show large ensemble spread, which is larger for $msDSI6_w$;

- Principal component (PC) analysis: For *msRAIN*, there is excellent consistency in the space-time covariance between the models and the observed data during both seasons. Spatial consistency is lacking between the models and the observed data for *msDSI6*, but better agreement across models;

- Bias in drought intensity (*DI*): Ensemble mean shows negative biases (within 27 %) for all regions for the DI_d under both moderate and extreme droughts. The DI_w on the other hand shows positive biases across the domain, with lower ensemble mean bias for extreme droughts (between 6 % and 17 %) compared with moderate droughts (>49 %). The ensemble spread is largest for DI_w under moderate drought conditions, whereas for all other conditions the ensemble spread is comparable;

- Bias in drought covariance index (*CI*): Except for Wales and Northern Ireland which show negative ensemble mean biases (within 2 %) for CI_w under moderate drought conditions, all other conditions are characterized by small positive biases (<14 %). However, larger positive bias is shown CI_d under extreme drought conditions (between 8 % and

25 %). Ensemble spread is considerably large in all cases, although smaller ensemble spread is shown for CI_w under moderate drought conditions;

- Bias in frequency of drought months (*FDM*): Negative ensemble mean bias (within 27 %) is shown for FDM_d, whereas positive bias (between 8 % and 34 %) is shown for FDM_w. The magnitudes of bias between the two drought severities are comparable. For all conditions, the ensemble spread is large;

- Bias in frequency of drought events at a given duration (*FDD*): Ensemble mean bias shows largely positive biases (<4 events) for FDD_3 and FDD_6 under both moderate and extreme drought conditions, whereas longer persistence durations (*i.e.*, FDD_{10} and FDD_{12}) are characterized by negative biases (within 1.8 events). The ensemble spread is relatively large for short persistence durations and generally decreases with increasing persistence duration; and

- Cross correlation analyses: Positive correlations are largely shown in the cross correlation between the 11-member ensemble for the bias in any given drought index and between the biases in wet season indices, hence indicating the consistency between the models (and between the wet season indices) in reproducing the spatial patterns of bias across all WRRs. High and statistically significant positive correlation is shown between the biases in *DI* and *msDSI6*, suggesting that the biases in *DI* (and *FDM*) are underpinned by the biases in *msDSI6*.

- Objective 4: *To examine the changes in 21st century drought characteristics in the UK projected by the UKMO RCMs.* Key results:

  - The projected ensemble-mean change for all drought characteristics shows similar spatial patterns between the 2050s and 2080s, compared to the 2020s. The magnitude of change is generally greater (and more widespread) for (i) moderate droughts and (ii) wet season compared with extreme droughts and the dry season, respectively;

  - Drought intensity (*DI*): Ensemble-mean change in *DI* for the 2080s shows decreases over Scotland and Wales, and increases over England and Northern Ireland during both dry and wet seasons and for moderate and extreme droughts. The highest increases (*DI* >20 %) are shown under moderate drought conditions for England during the wet season and Northern Ireland during both seasons. Maximum decreases

(*DI* ≥15 %) are shown for Scotland and Wales during the dry season under both moderate and extreme droughts. Maximum decrease in *DI* is also shown for Scotland during the wet season under moderate drought conditions. Model consensus shows greater agreement over most of England during the wet season but not during dry season;

- Drought covariance index (*CI*): Ensemble-mean change for the 2080s shows increases in *CI* in almost all regions during the wet and dry seasons under both drought severities. Greater magnitude of increase is shown during the dry season. The regions show higher covariance during extreme droughts (*CI* ≥18 %) compared with moderate droughts (*CI* ≥11 %). High model consensus covering large parts of the UK is prominent during the dry season under moderate drought conditions;

- Frequency of drought months (*FDM*): Ensemble-mean change for the 2080s shows decreases in *FDM* for Scotland and Wales. The decrease is larger during the dry season (3-4 % decrease in *FDM*) and for moderate droughts (7-9 % decrease in *FDM*) compared with the wet season and extreme droughts, respectively. England and Northern Ireland show increases in *FDM,* with highest increase (*FDM* ≥11 %) registered during the wet season. There is little difference in the magnitude of increase across the two drought severities. Good model consensus, characterizing most of England and Wales, is shown during the wet season under both drought severities. Larger area of no consensus, primarily over northern England, is shown during the dry season;

- Frequency of droughts at a given duration (*FDD*): Small change in *FDD* (±1 event per 30-years) for the 2080s is shown over most of the UK under both extreme and moderate drought conditions. Good model agreement is found over regions which exhibit increase in *FDD* and covers a larger part of the UK, especially England and Wales, under extreme drought conditions. Under extreme drought conditions, highest increase (2-4 events per 30-years) is largely found over Wales and southwest England for 3-month drought persistence duration. Greatest increase (3-5 events per 30-years) in *FDD* is shown under moderate droughts conditions and for 3-month drought persistence duration. These largely characterize almost all of England and Wales.

8.2 Implications of study on risk assessment for the UK

In January 2012, a climate change risk assessment (CCRA) report, which serves to inform the main risks and opportunities arising from climate change for 11 key sectors in the UK and to provide evidence to support decisions on adapting to climate change over the course of the next 100 years, was presented to the UK parliament (CCRA, 2012). The report identifies droughts as one of the climate change impact risks which can potentially influence the availability of water resources and cause disruptions to the food supply chain, ecosystems and human comfort, amongst others.

Much of the information on climate change projection that forms the basis of the CCRA report is derived from the UK Climate Projections 2009 (UKCP09), which is perceived as the standard for the UK. The UKCP09 focuses on climate change projections, such as the changes in seasonal temperature and precipitation for the 21st century. This limits our understanding of the potential impacts of these projections which encompass effects on human (and natural) systems and their adaptation capabilities. The scope of this thesis is not new. Work on the projected changes in droughts as a form of climate change impact has been studied by, for example, Vidal and Wade (2009), Burke *et al*. (2010), and the UK Met Office in their 2011 report, *Climate: Observations, projections and impacts*. Instead this thesis furthers our understanding of the behaviour of 21st century droughts by providing insights on new drought characteristics, and presenting opportunities to review existing water resource management practices which would benefit risk assessment in the UK. The implications of results of the thesis on risk assessment are summarized below;

- *Spatial distribution of droughts allows assessment of regional vulnerability*

  The central idea behind the analyses presented in the thesis is to assess how droughts are spatially distributed. This would facilitate assessment of regional vulnerability by identifying drought-risk, as well as drought-free, areas in the context of past experienced climate and future scenarios.

- *Drought characteristics offer insight on resource allocation priorities*

  In addition to identifying regional vulnerability, the thesis provides insights into the behaviour of droughts. Characteristics such as drought coherence, frequency of drought months and frequency of drought events at a given duration provide information on the length of time that an area remains in drought. Such information is essential for water resource management in that it allows prioritization of resource allocation.

- *Drought covariance index presents opportunity to review strategies in risk management*

  The new drought characteristic, the drought covariance index, offers the potential for adopting water transfers as one approach to drought management by supplying water to a drought area from those not experiencing simultaneous drought events. This approach provides a way to manage risk and reduce the vulnerability of an area to drought, and could serve as either an alternative or a complementary strategy to existing water management practices. Implementing water transfer, nonetheless, requires a feasibility assessment with the distance over which water will be transferred forming a key variable. Such information can be determined from the results of the thesis.

- *Seasonal influence on droughts points to the need for integrated regional water systems management*

  The vulnerability of a region to droughts is inherently tied to its water resource systems in which factors such as catchment characteristics (*e.g.*, land use), and anthropogenic effects (*e.g*., abstraction) may heighten or moderate the region's vulnerability. Regions which experience increases in drought risk during the wet season carry potential for prolonged drought episodes that may straddle the dry season especially when their water resource systems are dependent on wet season recharge, whereas regions experiencing increases in drought risk during the dry season may exert further stress on water resources. The seasonal influence on droughts, as this study has shown, points to the need for an integrated regional water systems management. This could include steps to towards better management of catchments (*e.g*., regulating the extent and type of land use/cover change), in addition to management of water resources (*e.g*., abstraction licenses and drought orders/permits) to enhance the region's resilience to droughts.

8.3 Limitations and recommendations for further work

Although this thesis has examined the changes in the characteristics of 21st century droughts in the UK incorporating also new aspects of droughts and novel methodologies, there are still possible avenues for further work.

One of the limitations of this study arises from the fact that while several aspects of river flow have been reproduced, there are other aspects notably intensity and duration that have been underestimated by the rainfall-based DSI. Future use of the DSI can introduce a transfer function to correct the discrepancy between the flow-based and rainfall-based DSI in order to obtain a more representative and reliable information for use in water resources management and planning.

The application of percentiles as used throughout the thesis presents only one approach from which the two drought severity conditions are classified. Further work to derive additional useful information could implement other statistical approaches such as Generalized Extreme Value Theory or introduce a severity classification scheme akin to those found in several drought indices such as the standardized precipitation index (SPI) and the Palmer drought severity index (PDSI).

Droughts often straddle seasons and as such the process of classifying them into seasons is complicated. Disaggregating the DSI data into months corresponding to the respective dry and wet seasons (*i.e.*, seasonal disaggregation) is a coarse guide to examining drought seasonality. Other ways to represent the seasonality of droughts could be explored.

The current approach of using the DSI assumes that the effect of evapotranspiration on future drought severity is not significant, presenting a worthy exercise for future work to investigate this assumption. Future work could also benefit from more sophisticated analyses such as using indices which factor in evaporative losses (*e.g.*, PDSI) or input climate data into gridded hydrological model. These approaches could provide more robust and reliable assessments of drought vulnerability.

The present research examines changes in drought characteristics for three 30-year future time periods (*i.e.*, 2020s, 2050s and 2080s). While the approach allows the assessment of drought risk in terms of short-, medium- and long-term scenarios, it also means that the evolution of droughts could not be captured. Future work addressing the temporal variability of droughts would allow better understanding of their development, cyclical patterns and decadal trends, which in turn would provide valuable information for drought forecast and management decisions.

Studies into future droughts could move beyond "evaluate and project" to looking at driving mechanisms, such as circulation types. This would offer an understanding of the physical basis of droughts and how they are represented in in global and regional climate models, hence providing insights on their limitations.

There are a number of caveats with using datasets from the PPE experiment in impacts assessment. Here, a brief summary of the limitations, drawing upon detailed discussions from Murphy *et al*. (2004; 2007; 2009) and Fung *et al*. (2011), are given. First, the application of the HadRM3-PPE-UK provides only a small range of possible outcomes of future climates (*i.e*., 11 scenarios) for impacts assessment. Although this is a significant shift from the traditional method of using a single climate model for simulation of future climates, the HadRM3-PPE-UK does not sample the full range of modeling uncertainties which could provide a wider range of possible outcomes.

Second, the HadRM3-PPE-UK only represents projections from the HadCM3 and does not incorporate projections from other GCMs. This means that structural errors, which could either narrow or widen the uncertainties, are not sampled.

Third, as with all climate models, the HadRM3-PPE-UK has inherent bias which needs to be addressed. The objectives of the present study could be repeated in its entirety but using HadRM3-PPE-UK data which have been bias-corrected. This would make an interesting comparison to see if uncertainties in simulating present day droughts are reduced when a bias-corrected precipitation dataset is used. Although bias correction has considerable influence on model results, it can be problematic as every bias correction technique has its caveats (*e.g*., standardizing the model against the observed climatology captures the mean statistics, and not extremes). In addition, bias correction does not provide a satisfactory physical justification and is unable to correct temporal errors in atmospheric circulation systems (*e.g*., onset of monsoons) which drive some of the core climatic variables such as precipitation. Ehret *et al*.

(2012) argues that bias correction "*hides rather than reduces uncertainties, which may lead to avoidable forejudging of end user and decision makers*".

Forth, it is assumed that the medium (A1B) emissions scenario, on which climate projections by the HadRM3-PPE-UK is based, is adequate for impacts assessment and decision making. Robust assessment of impacts would require projections based on other SRES emissions scenarios (*i.e.,* A1FI, A1T, A2, B1 and B2) and the newer greenhouse gas concentration trajectories, the representative concentration pathways (RCPs).

8.4 Concluding remarks

The impacts of droughts can be felt through all sectors, ranging from ecosystems to economy and from agriculture to human comfort. While the prediction of droughts remains a core challenge in drought science, tools such as drought indices are available to provide a reasonable level of detectability. The vulnerability of a region to droughts requires not only a good understanding of the behavior of droughts; it also requires an evaluation of water resource management practices, which can serve to mitigate or further exacerbate its vulnerability. Past drought events in the UK have provided valuable lessons from which existing and future management and planning decisions can be based on. It is hoped that this thesis, despite its limited capacity, can serve to inform the nature of 21st century droughts in the UK so that better risk assessment and management considerations can be made in light of future anthropogenic climate change.

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Appendix A – List o*f* Tables

Table A-1: Common drought months between $MGR_{DSI\text{-}n}$ and lagged $MRF_{DSI\text{-}n}$ for the Dove catchment during the (a) dry and (b) wet seasons. Values greater than lag 0 are underlined. p>95, p>90, p>70, and p>55 indicate the 95th, 90th, 70th and 55th percentile threshold exceedance, respectively.

	DSI3				DSI6				DSI12				DSI24			
	p>95	*p*>90	*p*>70	*p*>55	*p*>95	*p*>90	*p*>70	*p*>55	*p*>95	*p*>90	*p*>70	*p*>55	*p*>95	*p*>90	*p*>70	*p*>55
(a) Dry season																
Lag 0	66.7	65.2	50.8	58.0	83.3	73.9	63.6	68.0	27.3	68.2	57.6	64.9	54.6	63.6	78.1	70.8
Lag 1	63.6	59.1	57.6	63.6	81.8	72.7	60.6	67.7	36.4	68.2	65.2	70.2	54.6	59.1	79.7	73.7
Lag 2	54.6	54.6	56.1	58.6	81.8	68.2	59.1	61.6	45.5	68.2	70.8	71.3	54.6	57.1	81.0	71.6
Lag 3	45.5	40.9	43.9	54.6	63.6	59.1	53.0	52.5	54.6	68.2	67.7	69.2	45.5	57.1	77.8	68.4
Lag 4	36.4	36.4	33.3	49.0	54.6	50.0	42.4	45.9	63.6	63.6	61.5	66.0	27.3	61.9	73.0	67.0
Lag 5	27.3	36.4	36.9	52.0	45.5	40.9	40.0	49.0	72.7	54.6	54.7	63.4	18.2	52.4	66.7	62.8
Lag 6	18.2	40.9	47.7	53.6	36.4	31.8	49.2	56.7	72.7	45.5	53.1	58.7	27.3	47.6	64.5	59.1
(b) Wet season																
Lag 0	50.0	47.8	47.1	53.5	50.0	69.6	62.7	55.0	54.6	77.3	65.2	63.6	63.6	63.6	75.0	65.3
Lag 1	58.3	69.6	55.2	57.4	54.6	77.3	63.6	55.6	54.6	81.8	68.2	68.2	72.7	68.2	75.0	66.0
Lag 2	66.7	69.6	50.8	53.0	54.6	77.3	60.6	51.5	63.6	77.3	63.1	62.5	54.6	61.9	76.2	66.7
Lag 3	66.7	56.5	41.8	47.0	54.6	77.3	57.6	49.5	63.6	68.2	61.5	61.4	36.4	57.1	74.6	67.4
Lag 4	72.7	45.5	34.9	39.4	54.6	77.3	56.1	48.0	45.5	59.1	60.0	55.7	27.3	42.9	73.0	69.2
Lag 5	72.7	45.5	36.4	38.4	45.5	72.7	52.3	48.0	45.5	50.0	57.8	53.4	27.3	47.6	69.8	68.9
Lag 6	63.6	45.5	42.4	42.4	63.6	68.2	50.8	49.5	45.5	45.5	54.7	50.0	27.3	47.6	69.4	66.3

Table A-2: As Table A-1, but for the Lud catchment.

	DSI3				DSI6				DSI12				DSI24			
	p>95	*p*>90	*p*>70	*p*>55	*p*>95	*p*>90	*p*>70	*p*>55	*p*>95	*p*>90	*p*>70	*p*>55	*p*>95	*p*>90	*p*>70	*p*>55
(a) Dry season																
Lag 0	66.7	52.2	69.6	69.9	75.0	47.8	78.3	80.0	50.0	56.5	76.5	73.3	36.4	86.4	86.4	92.1
Lag 1	75.0	56.5	73.5	68.6	75.0	52.2	79.4	80.0	58.3	65.2	80.6	77.2	45.5	90.9	89.4	92.1
Lag 2	83.3	52.2	75.0	71.6	75.0	56.5	82.4	77.9	66.7	73.9	82.1	83.0	54.6	81.8	87.7	92.1
Lag 3	75.0	47.8	72.1	71.3	66.7	56.5	79.4	73.7	75.0	87.0	82.1	83.0	54.6	68.2	87.7	91.0
Lag 4	66.7	47.8	64.2	64.4	58.3	56.5	70.2	65.3	81.8	81.8	81.8	78.8	45.5	59.1	87.7	89.9
Lag 5	58.3	47.8	55.2	59.0	50.0	56.5	65.7	61.1	90.9	77.3	80.3	73.7	36.4	54.6	85.9	87.6
Lag 6	50.0	43.5	47.8	55.0	41.7	52.2	59.7	61.1	90.9	72.7	80.3	70.7	36.4	45.5	81.3	84.3
(b) Wet season																
Lag 0	50.0	47.8	47.8	56.7	50.0	30.4	47.8	59.2	33.3	56.5	70.6	78.4	36.4	63.6	75.8	85.9
Lag 1	58.3	56.5	56.5	64.4	50.0	34.8	57.4	67.7	41.7	60.9	75.0	82.2	36.4	68.2	80.3	88.9
Lag 2	66.7	60.9	66.7	68.9	50.0	39.1	64.7	73.5	50.0	65.2	77.6	82.2	36.4	68.2	83.3	89.8
Lag 3	75.0	60.9	68.1	66.0	50.0	43.5	70.6	71.3	58.3	69.6	79.1	80.0	27.3	68.2	84.6	89.8
Lag 4	75.0	65.2	70.6	63.7	50.0	52.2	71.6	64.4	66.7	69.6	80.6	77.0	27.3	72.7	87.7	89.7
Lag 5	66.7	69.6	61.8	54.9	50.0	60.9	70.2	63.0	72.7	72.7	83.3	72.7	9.1	77.3	87.7	87.6
Lag 6	58.3	73.9	58.8	52.5	50.0	65.2	65.7	60.0	72.7	72.7	83.3	69.7	9.1	68.2	87.5	85.4

Table A-3: Cross correlation, across all WRRs, between the biases in the drought indices during the dry and wet seasons under moderate drought conditions for each ensemble member (afgcx to afixq). *DI* = drought intensity; *CI* = drought covariance index; *FDM* = frequency of drought months; *msRAIN* = mean seasonal rainfall; *msDSI6* = mean seasonal DSI6. Values with statistically significant correlation at the 90 % confidence level are underlined. Figures in parentheses show the climate sensitivity (K) of corresponding HadSM3 variant for each ensemble member. Subscripts d and w refer to the dry and wet seasons, respectively.

	CI_{d}	FDM_{d}	$msRAIN_{\mathrm{d}}$	$msDSI6_{\mathrm{d}}$	DI_{w}	CI_{w}	FDM_{w}	$msRAIN_{\mathrm{w}}$	$msDSI6_{\mathrm{w}}$
afgcx (3.53 K)									
DI_{d}	-0.64	0.74	-0.09	0.95	-0.01	-0.06	-0.74	-0.67	0.50
CI_{d}		-0.52	0.15	-0.65	-0.1	0.48	0.45	0.71	-0.34
FDM_{d}			-0.12	0.62	-0.45	-0.12	-0.92	-0.74	-0.07
$msRAIN_{\mathrm{d}}$				-0.17	-0.06	-0.34	0.08	0.45	-0.17
$msDSI6_{\mathrm{d}}$					0.18	-0.05	-0.61	-0.64	0.69
DI_{w}						-0.01	0.56	0.2	0.68
CI_{w}							0	0.24	0.11
FDM_{w}								0.72	0.04
$msRAIN_{\mathrm{w}}$									-0.2
afixa (2.58 K)									
DI_{d}	-0.45	0.52	-0.29	0.92	-0.05	-0.38	-0.47	-0.46	0.25
CI_{d}		-0.60	0.34	-0.34	0.19	0.22	0.37	0.54	0.32
FDM_{d}			-0.40	0.45	-0.59	0.26	-0.88	-0.52	-0.49
$msRAIN_{\mathrm{d}}$				-0.38	0.06	0.03	0.29	0.66	0.14
$msDSI6_{\mathrm{d}}$					0.08	-0.45	-0.42	-0.42	0.36
DI_{w}						-0.57	0.80	0.38	0.56
CI_{w}							-0.41	0.13	-0.62
FDM_{w}								0.48	0.40
$msRAIN_{\mathrm{w}}$									0.14
afixc (2.81 K)									
DI_{d}	-0.05	0.14	-0.08	0.77	-0.01	-0.06	-0.41	0.17	0.63
CI_{d}		-0.48	-0.02	-0.15	0.17	0.69	0.31	0.40	0.15
FDM_{d}			0.01	0.17	-0.66	-0.49	-0.78	-0.31	-0.46
$msRAIN_{\mathrm{d}}$				0.01	0.03	-0.13	0.16	0.55	-0.02
$msDSI6_{\mathrm{d}}$					0.18	-0.19	-0.34	0.09	0.62
DI_{w}						0.18	0.76	0.36	0.48
CI_{w}							0.3	0.2	0.08
FDM_{w}								0.41	0.17
$msRAIN_{\mathrm{w}}$									0.2

afixh (3.43 K)

DI_{d}	-0.77	0.63	0.1	0.92	0.52	-0.34	-0.60	-0.15	0.68
CI_{d}		-0.44	0.03	-0.82	-0.47	0.33	0.40	0.22	-0.57
FDM_{d}			-0.22	0.59	-0.15	0	-0.97	-0.56	0.1
$msRAIN_{d}$				-0.03	0.1	-0.27	0.25	0.63	0.03
$msDSI6_{d}$					0.50	-0.37	-0.58	-0.34	0.77
DI_{w}						-0.19	0.22	0.22	0.66
CI_{w}							-0.02	0	-0.38
FDM_{w}								0.63	-0.1
$msRAIN_{w}$									-0.01

afixi (4.39 K)

DI_{d}	-0.51	0.43	0.14	0.87	0.29	-0.26	-0.34	-0.05	0.12
CI_{d}		-0.72	-0.22	-0.48	0.13	0.52	0.57	0.47	0.52
FDM_{d}			0.06	0.53	-0.46	-0.26	-0.93	-0.62	-0.65
$msRAIN_{d}$				0.01	0.1	-0.26	0	0.33	-0.27
$msDSI6_{d}$					0.17	-0.33	-0.44	-0.24	0.13
DI_{w}						-0.05	0.71	0.67	0.73
CI_{w}							0.12	0.21	0.25
FDM_{w}								0.66	0.66
$msRAIN_{w}$									0.62

afixj (3.89 K)

DI_{d}	-0.05	-0.28	-0.3	0.84	0.29	0	-0.05	-0.05	0.60
CI_{d}		-0.54	-0.44	-0.33	0.12	0.81	0.38	0.28	0.25
FDM_{d}			0.53	-0.06	-0.78	-0.52	-0.72	-0.70	-0.80
$msRAIN_{d}$				-0.19	-0.26	-0.54	-0.15	-0.11	-0.44
$msDSI6_{d}$					0.23	-0.28	-0.12	-0.17	0.51
DI_{w}						-0.01	0.84	0.68	0.74
CI_{w}							0.29	0.31	0.32
FDM_{w}								0.68	0.53
$msRAIN_{w}$									0.57

afixk (4.44 K)

DI_{d}	-0.59	0.32	-0.07	0.92	-0.01	-0.2	-0.48	-0.44	0.19
CI_{d}		-0.69	-0.26	-0.59	0.23	0.52	0.57	0.37	0.34
FDM_{d}			0.35	0.31	-0.68	-0.58	-0.78	-0.66	-0.76
$msRAIN_{d}$				-0.09	-0.02	-0.46	0.03	0.22	-0.39
$msDSI6_{d}$					0.07	-0.28	-0.42	-0.41	0.28
DI_{w}						0.23	0.82	0.61	0.66
CI_{w}							0.46	0.08	0.28
FDM_{w}								0.76	0.45
$msRAIN_{w}$									0.38

afixl (4.88 K)									
DI_d	-0.15	0.03	0.34	0.75	0.36	-0.12	-0.14	0.04	0.46
CI_d		-0.89	-0.31	0.3	0.54	0.05	0.87	0.71	0.69
FDM_d			0.24	-0.32	-0.68	0.07	-0.96	-0.72	-0.74
$msRAIN_d$				0.11	0.19	-0.28	-0.18	0.13	-0.06
$msDSI6_d$					0.48	-0.26	0.22	0.31	0.79
DI_w						-0.16	0.72	0.73	0.70
CI_w							-0.17	-0.07	-0.05
FDM_w								0.72	0.66
$msRAIN_w$									0.64
afixm (4.54 K)									
DI_d	-0.32	0.22	-0.08	0.90	0.16	-0.15	-0.3	-0.2	0.40
CI_d		-0.86	-0.39	-0.2	0.65	0.49	0.81	0.65	0.58
FDM_d			0.24	0.15	-0.81	-0.26	-0.97	-0.68	-0.68
$msRAIN_d$				-0.22	-0.15	-0.29	-0.13	0.14	-0.44
$msDSI6_d$					0.16	-0.23	-0.23	-0.18	0.51
DI_w						0.24	0.79	0.72	0.68
CI_w							0.18	0.39	0.01
FDM_w								0.72	0.61
$msRAIN_w$									0.35
afixo (4.79 K)									
DI_d	-0.66	0.64	-0.19	0.93	0.67	-0.54	-0.60	-0.48	0.67
CI_d		-0.81	0.14	-0.62	-0.22	0.77	0.71	0.68	-0.18
FDM_d			-0.3	0.58	0.01	-0.52	-0.94	-0.79	0.04
$msRAIN_d$				-0.14	0.03	0.19	0.31	0.61	0.05
$msDSI6_d$					0.72	-0.53	-0.54	-0.37	0.79
DI_w						-0.24	0.11	0.12	0.90
CI_w							0.42	0.54	-0.26
FDM_w								0.81	-0.02
$msRAIN_w$									0.06
afixq (7.11 K)									
DI_d	-0.49	0.53	0.05	0.75	-0.19	-0.04	-0.64	-0.54	-0.24
CI_d		-0.86	-0.55	-0.15	0.70	0.27	0.79	0.69	0.79
FDM_d			0.45	0.28	-0.81	-0.25	-0.94	-0.70	-0.81
$msRAIN_d$				-0.21	-0.40	-0.44	-0.33	0.04	-0.57
$msDSI6_d$					-0.03	0.01	-0.43	-0.33	0.2
DI_w						0.17	0.82	0.65	0.80
CI_w							0.21	0.19	0.26
FDM_w								0.73	0.71
$msRAIN_w$									0.64

Table A-4: Cross correlation, across all WRRs, between the 11-member ensemble (afgcx to afixq) for the bias in mean seasonal rainfall (*msRAIN*) during the dry (a) and wet (b) seasons. * shows statistically significant correlation at the 90 % confidence level.

	afixa	afixc	afixh	afixi	afixj	afixk	afixl	afixm	afixo	afixq
a) Dry season										
afgcx	0.73*	0.72*	0.93*	0.64*	0.19	0.33	0.62*	0.50*	0.72*	-0.01
afixa		0.88*	0.77*	0.77*	0.46*	0.56*	0.65*	0.66*	0.71*	0.25
afixc			0.76*	0.88*	0.58*	0.73*	0.74*	0.77*	0.79*	0.41*
afixh				0.63*	0.22	0.36*	0.64*	0.56*	0.86*	0.03
afixi					0.74*	0.87*	0.80*	0.82*	0.68*	0.61*
afixj						0.90*	0.73*	0.82*	0.31	0.91*
afixk							0.75*	0.86*	0.50*	0.82*
afixl								0.87*	0.65*	0.65*
afixm									0.66*	0.74*
afixo										0.25
b) Wet season										
afgcx	0.91*	0.89*	0.93*	0.93*	0.91*	0.90*	0.94*	0.91*	0.92*	0.87*
afixa		0.91*	0.93*	0.91*	0.84*	0.88*	0.82*	0.87*	0.85*	0.86*
afixc			0.84*	0.89*	0.92*	0.94*	0.91*	0.87*	0.87*	0.79*
afixh				0.91*	0.80*	0.80*	0.87*	0.89*	0.90*	0.87*
afixi					0.83*	0.88*	0.89*	0.97*	0.94*	0.97*
afixj						0.94*	0.91*	0.77*	0.81*	0.71*
afixk							0.87*	0.82*	0.85*	0.79*
afixl								0.89*	0.94*	0.81*
afixm									0.96*	0.96*
afixo										0.91*

Table A-5: As Table A-4, but for mean seasonal DSI6 bias (*msDSI6*).

	afixa	afixc	afixh	afixi	afixj	afixk	afixl	afixm	afixo	afixq
a) Dry season										
afgcx	0.55*	0.39*	0.39*	0.44*	0.31	0.63*	0.1	0.46*	0.61*	0.62*
afixa		0.34	0.19	0.1	0.61*	0.70*	0.15	0.55*	0.31	0.48*
afixc			0.47*	0.52*	0.19	0.29	0.48*	0.67*	0.22	0.69*
afixh				0.81*	-0.21	0.04	0.3	0.62*	0.64*	0.50*
afixi					-0.15	0.1	0.28	0.61*	0.70*	0.47*
afixj						0.78*	0.25	0.27	0.07	0.42*
afixk							0.18	0.43*	0.40*	0.50*
afixl								0.62*	-0.14	0.62*
afixm									0.26	0.74*
afixo										0.29
b) Wet season										
afgcx	0.2	0.54*	0.52*	0.2	0.26	0.36*	-0.03	0.13	0.56*	0.24
afixa		0.47*	0.38*	0.47*	0.62*	0.63*	0.64*	0.64*	0.17	0.55*
afixc			0.64*	0.64*	0.53*	0.53*	0.45*	0.59*	0.33	0.57*
afixh				0.35	0.21	0.21	0.26	0.48*	0.65*	0.3
afixi					0.82*	0.70*	0.65*	0.72*	0.22	0.83*
afixj						0.89*	0.74*	0.70*	0.1	0.85*
afixk							0.62*	0.67*	0.1	0.85*
afixl								0.90*	-0.08	0.64*
afixm									0.09	0.70*
afixo										0.03

Table A-6: Cross correlation, across all WRRs, between the 11-member ensemble (afgcx to afixq) for the bias in drought intensity (*DI*) during the dry and wet seasons and under both moderate and extreme drought conditions. * shows statistically significant correlation at the 90 % confidence level.

	afixa	afixc	afixh	afixi	afixj	afixk	afixl	afixm	afixo	afixq
(a) Dry season: Moderate droughts										
afgcx	0.62*	0.15	0.38*	0.43*	0.13	0.64*	0.61*	0.64*	0.68*	0.82*
afixa		0.22	-0.03	0.05	0.49*	0.73*	0.09	0.53*	0.42*	0.58*
afixc			0.19	0.17	0.55*	0.22	0.32	0.48*	-0.2	0.36*
afixh				0.81*	-0.16	0.05	0.54*	0.61*	0.50*	0.46*
afixi					0.07	0.3	0.55*	0.66*	0.63*	0.54*
afixj						0.66*	0.1	0.43*	-0.02	0.3
afixk							0.29	0.70*	0.53*	0.73*
afixl								0.64*	0.23	0.57*
afixm									0.45*	0.83*
afixo										0.62*
(b) Dry season: Extreme droughts										
afgcx	0.63*	0.36*	0.53*	0.43*	0.36*	0.67*	0.07	0.36*	0.62*	0.74*
afixa		0.48*	0.56*	0.47*	0.42*	0.58*	0.11	0.53*	0.54*	0.58*
afixc			0.42*	0.43*	0.21	0.21	0.35*	0.60*	0.22	0.66*
afixh				0.89*	-0.14	0.1	0.34	0.56*	0.73*	0.56*
afixi					-0.1	0.11	0.27	0.48*	0.72*	0.51*
afixj						0.79*	-0.13	0.16	0.11	0.27
afixk							-0.09	0.22	0.41*	0.44*
afixl								0.63*	-0.18	0.36*
afixm									0.1	0.54*
afixo										0.42*
(c) Wet season: Moderate droughts										
afgcx	0.69*	0.84*	0.83*	0.81*	0.76*	0.82*	0.43*	0.62*	0.82*	0.74*
afixa		0.76*	0.63*	0.83*	0.89*	0.90*	0.63*	0.62*	0.66*	0.70*
afixc			0.80*	0.86*	0.81*	0.84*	0.51*	0.58*	0.80*	0.69*
afixh				0.77*	0.71*	0.75*	0.46*	0.67*	0.81*	0.70*
afixi					0.90*	0.92*	0.65*	0.77*	0.70*	0.79*
afixj						0.98*	0.77*	0.82*	0.60*	0.88*
afixk							0.68*	0.79*	0.65*	0.87*
afixl								0.88*	0.33	0.63*
afixm									0.40*	0.81*
afixo										0.45*

(d) Wet season: Extreme droughts

afgcx	0.03	0.46*	0.41*	0.14	0.3	0.39*	0	0.07	0.37*	0.27
afixa		0.46*	0.3	0.45*	0.61*	0.46*	0.45*	0.58*	0.18	0.57*
afixc			0.59*	0.53*	0.46*	0.54*	0.51*	0.65*	0.12	0.52*
afixh				0.42*	0.08	-0.04	0.14	0.32	0.70*	0.04
afixi					0.44*	0.24	0.57*	0.74*	0.31	0.56*
afixj						0.78*	0.63*	0.53*	-0.1	0.82*
afixk							0.56*	0.54*	-0.28	0.73*
afixl								0.74*	-0.27	0.74*
afixm									-0.03	0.67*
afixo										-0.27

Table A-7: Cross correlation, across all WRRs, between the 11-member ensemble (afgcx to afixq) for the bias in drought covariance index (*CI*) during the dry and wet seasons and under both moderate and extreme drought conditions. * shows statistically significant correlation at the 90 % confidence level.

	afixa	afixc	afixh	afixi	afixj	afixk	afixl	afixm	afixo	afixq
(a) Dry season: Moderate droughts										
afgcx	0.87*	0.57*	0.33	0.74*	0.61*	0.83*	0.62*	0.78*	0.79*	0.73*
afixa		0.55*	0.21	0.68*	0.50*	0.73*	0.60*	0.68*	0.78*	0.71*
afixc			0.40*	0.55*	0.46*	0.53*	0.58*	0.55*	0.68*	0.71*
afixh				0.49*	0.05	0.25	0.21	0.2	0.3	0.24
afixi					0.47*	0.64*	0.75*	0.78*	0.76*	0.75*
afixj						0.74*	0.51*	0.65*	0.64*	0.50*
afixk							0.56*	0.75*	0.77*	0.73*
afixl								0.85*	0.83*	0.88*
afixm									0.80*	0.87*
afixo										0.90*
(b) Dry season: Extreme droughts										
afgcx	0.65*	0.56*	0.37*	0.34	0.58*	0.69*	0.65*	0.40*	0.81*	0.58*
afixa		0.60*	0.60*	0.33	0.47*	0.50*	0.40*	0.47*	0.84*	0.48*
afixc			0.59*	0.37*	0.21	0.63*	0.55*	0.71*	0.54*	0.22
afixh				0.47*	-0.08	0.35	0.27	0.69*	0.58*	0.26
afixi					0.29	0.58*	0.25	0.70*	0.47*	0.47*
afixj						0.52*	0.45*	0.07	0.51*	0.51*
afixk							0.56*	0.50*	0.62*	0.73*
afixl								0.50*	0.57*	0.39*
afixm									0.47*	0.21
afixo										0.69*
(c) Wet season: Moderate droughts										
afgcx	0.56*	0.40*	0.21	0.39*	0.68*	0.41*	0.43*	0.41*	0.45*	0.32
afixa		0.37*	0.49*	0.21	0.29	0.04	0.59*	0.40*	0.32	0.05
afixc			0.39*	0.24	0.46*	0.56*	0.31	0.51*	0.48*	-0.01
afixh				0.08	-0.24	-0.13	0.36*	0.38*	-0.1	-0.15
afixi					0.26	0.03	0.2	0.46*	0.48*	0.12
afixj						0.61*	0.41*	0.33	0.69*	0.42*
afixk							0.32	0.21	0.28	0.29
afixl								0.34	0.3	0.18
afixm									0.59*	0.21
afixo										0.12

(d) Wet season: Extreme droughts

afgcx	0.50*	0.21	0.25	0.45*	0.82*	0.46*	0.81*	0.58*	0.63*	0.76*
afixa		0.72*	0.34	0.65*	0.45*	0.68*	0.62*	0.75*	0.74*	0.56*
afixc			0.64*	0.59*	0.24	0.38*	0.53*	0.76*	0.23	0.28
afixh				0.50*	0.33	0.25	0.46*	0.65*	0.1	0.22
afixi					0.67*	0.61*	0.58*	0.81*	0.48*	0.57*
afixj						0.46*	0.84*	0.67*	0.59*	0.88*
afixk							0.48*	0.62*	0.57*	0.53*
afixl								0.77*	0.55*	0.81*
afixm									0.46*	0.56*
afixo										0.66*

Table A-8: Cross correlation, across all WRRs, between the 11-member ensemble (afgcx to afixq) for the bias in frequency of drought months (*FDM*) during the dry and wet seasons and under both moderate and extreme drought conditions. * shows statistically significant correlation at the 90 % confidence level.

	afixa	afixc	afixh	afixi	afixj	afixk	afixl	afixm	afixo	afixq
(a) Dry season: Moderate droughts										
afgcx	0.33	0.41*	0.79*	0.83*	0.67*	0.76*	0.76*	0.74*	0.84*	0.88*
afixa		0.60*	0.27	0.52*	0.71*	0.64*	0.62*	0.74*	0.61*	0.48*
afixc			0.34	0.53*	0.66*	0.58*	0.45*	0.55*	0.53*	0.60*
afixh				0.84*	0.58*	0.66*	0.62*	0.64*	0.68*	0.74*
afixi					0.80*	0.87*	0.83*	0.85*	0.89*	0.91*
afixj						0.91*	0.85*	0.90*	0.87*	0.85*
afixk							0.86*	0.92*	0.93*	0.95*
afixl								0.90*	0.93*	0.85*
afixm									0.92*	0.87*
afixo										0.93*
(b) Dry season: Extreme droughts										
afgcx	0.80*	0.74*	0.73*	0.81*	0.63*	0.78*	0.75*	0.71*	0.74*	0.89*
afixa		0.61*	0.47*	0.82*	0.62*	0.77*	0.69*	0.78*	0.71*	0.79*
afixc			0.63*	0.69*	0.60*	0.69*	0.80*	0.61*	0.72*	0.67*
afixh				0.65*	0.19	0.39*	0.56*	0.67*	0.52*	0.73*
afixi					0.69*	0.83*	0.83*	0.86*	0.90*	0.88*
afixj						0.87*	0.60*	0.45*	0.77*	0.59*
afixk							0.75*	0.65*	0.82*	0.77*
afixl								0.81*	0.77*	0.73*
afixm									0.67*	0.74*
afixo										0.85*
(c) Wet season: Moderate droughts										
afgcx	0.47*	0.48*	0.73*	0.85*	0.60*	0.72*	0.73*	0.74*	0.82*	0.86*
afixa		0.80*	0.26	0.60*	0.88*	0.76*	0.62*	0.69*	0.57*	0.54*
afixc			0.23	0.55*	0.84*	0.69*	0.44*	0.48*	0.39*	0.53*
afixh				0.78*	0.36*	0.50*	0.65*	0.71*	0.69*	0.71*
afixi					0.72*	0.82*	0.89*	0.88*	0.89*	0.93*
afixj						0.90*	0.69*	0.74*	0.69*	0.71*
afixk							0.75*	0.83*	0.80*	0.88*
afixl								0.87*	0.92*	0.81*
afixm									0.89*	0.86*
afixo										0.89*

(d) Wet season: Extreme droughts

afgcx	0.79*	0.72*	0.73*	0.85*	0.60*	0.74*	0.71*	0.71*	0.75*	0.90*
afixa		0.70*	0.41*	0.85*	0.78*	0.79*	0.74*	0.75*	0.80*	0.75*
afixc			0.61*	0.76*	0.55*	0.67*	0.80*	0.70*	0.71*	0.71*
afixh				0.66*	0.13	0.29	0.55*	0.65*	0.49*	0.72*
afixi					0.74*	0.81*	0.85*	0.87*	0.92*	0.91*
afixj						0.93*	0.62*	0.53*	0.82*	0.62*
afixk							0.69*	0.62*	0.86*	0.73*
afixl								0.85*	0.78*	0.73*
afixm									0.71*	0.72*
afixo										0.86*

Table A-9: Cross correlation, across all WRRs, between the 11-member ensemble (afgcx to afixq) for the bias in the frequency of drought events at a given duration (*FDD*) for moderate droughts with persistence of at least 3 (FDD_3), 6 (FDD_6), 10 (FDD_{10}) and 12 (FDD_{12}) months. * shows statistically significant correlation at the 90 % confidence level.

	afixa	afixc	afixh	afixi	afixj	afixk	afixl	afixm	afixo	afixq
(a) *FDD*3										
afgcx	0.64*	0.56*	0.86*	0.80*	0.21	0.38*	0.52*	0.63*	0.74*	0.66*
afixa		0.62*	0.57*	0.76*	0.22	0.35	0.55*	0.66*	0.69*	0.50*
afixc			0.53*	0.64*	0.46*	0.74*	0.68*	0.56*	0.63*	0.62*
afixh				0.84*	0.18	0.36*	0.54*	0.72*	0.73*	0.60*
afixi					0.11	0.47*	0.65*	0.76*	0.73*	0.74*
afixj						0.62*	0.38*	0.13	0.54*	0.41*
afixk							0.55*	0.36*	0.62*	0.72*
afixl								0.61*	0.57*	0.59*
afixm									0.54*	0.55*
afixo										0.71*
(b) *FDD*6										
afgcx	0.24	0.26	0.29	0.49*	0.15	0.18	0.3	0.29	0.29	0.21
afixa		0.69*	0.38*	0.57*	0.46*	0.57*	0.17	0.40*	0.54*	0.42*
afixc			0.37*	0.33	0.67*	0.67*	0.49*	0.45*	0.65*	0.72*
afixh				0.38*	0.25	0.57*	0.17	0.71*	0.40*	0.17
afixi					0.47*	0.56*	0.09	0.35*	0.67*	0.40*
afixj						0.72*	0.03	0.29	0.71*	0.67*
afixk							0.11	0.50*	0.75*	0.63*
afixl								0.52*	0.28	0.52*
afixm									0.33	0.3
afixo										0.71*
(c) *FDD*10										
afgcx	0.45*	0.38*	0.55*	0.21	0.02	0.14	0.54*	0.41*	0.21	0.28
afixa		0.68*	0.81*	0.78*	0.34	0.46*	0.54*	0.66*	0.57*	0.65*
afixc			0.66*	0.78*	0.68*	0.80*	0.44*	0.72*	0.77*	0.71*
afixh				0.77*	0.45*	0.57*	0.40*	0.62*	0.69*	0.65*
afixi					0.52*	0.70*	0.46*	0.73*	0.77*	0.77*
afixj						0.82*	-0.02	0.46*	0.79*	0.38*
afixk							0.27	0.46*	0.90*	0.68*
afixl								0.47*	0.35	0.53*
afixm									0.50*	0.55*
afixo										0.66*

(d) FDD_{12}

afgcx	0.58*	0.64*	0.73*	0.61*	0.31	0.46*	0.57*	0.57*	0.53*	0.59*
afixa		0.75*	0.84*	0.73*	0.43*	0.50*	0.48*	0.80*	0.68*	0.69*
afixc			0.73*	0.79*	0.75*	0.75*	0.52*	0.63*	0.82*	0.80*
afixh				0.75*	0.39*	0.48*	0.60*	0.78*	0.74*	0.73*
afixi					0.51*	0.56*	0.57*	0.71*	0.76*	0.79*
afixj						0.89*	0.16	0.26	0.74*	0.62*
afixk							0.22	0.26	0.76*	0.64*
afixl								0.60*	0.45*	0.29
afixm									0.51*	0.58*
afixo										0.78*

Table A-10: As Table A-9, but for extreme droughts.

	afixa	afixc	afixh	afixi	afixj	afixk	afixl	afixm	afixo	afixq
(a) *FDD*$_3$										
afgcx	0.63*	0.74*	0.16	0.46*	0.59*	0.47*	0.18	0.35	0.65*	0.13
afixa		0.53*	0.13	0.55*	0.67*	0.72*	0.26	0.58*	0.72*	0.29
afixc			0.01	0.34	0.44*	0.37*	0.33	0.35*	0.36*	0.08
afixh				-0.05	-0.03	-0.07	0.31	0.21	0.13	0.34
afixi					0.18	0.59*	0.07	0.60*	0.61*	0.03
afixj						0.53*	0.08	0.23	0.55*	0.26
afixk							0	0.46*	0.71*	0.14
afixl								0.3	0.09	0.66*
afixm									0.46*	0.12
afixo										0.34
(b) *FDD*$_6$										
afgcx	0.18	0.44*	0.55*	0.29	0.02	0.25	0.61*	0.19	0.01	0.32
afixa		0.54*	0.35	0.09	0.02	0.25	0.54*	0.38*	0.42*	0.42*
afixc			0.64*	0.45*	0.39*	0.74*	0.64*	0.66*	0.67*	0.44*
afixh				0.13	0.52*	0.62*	0.64*	0.16	0.62*	0.67*
afixi					0.08	0.39*	0.3	0.26	0.24	0.35*
afixj						0.73*	0.12	0.18	0.73*	0.43*
afixk							0.58*	0.43*	0.82*	0.64*
afixl								0.24	0.53*	0.60*
afixm									0.3	0.08
afixo										0.63*
(c) *FDD*$_{10}$										
afgcx	0.44*	0.66*	0.51*	0.43*	0.69*	0.69*	0.58*	0.34	0.62*	0.28
afixa		0.27	0.47*	0.48*	0.2	0.55*	0.65*	0.63*	0.49*	0.42*
afixc			0.15	0.25	0.79*	0.60*	0.18	0.21	0.68*	0.11
afixh				0.56*	0.17	0.35*	0.41*	0.67*	0.46*	0.24
afixi					0.2	0.48*	0.29	0.64*	0.57*	0.31
afixj						0.55*	0.14	0.38*	0.74*	0.32
afixk							0.41*	0.39*	0.57*	0.25
afixl								0.35	0.19	0.54*
afixm									0.66*	0.55*
afixo										0.28
(d) *FDD*$_{12}$										
afgcx	0.22	0.57*	0.48*	0.11	0.56*	0.45*	0.07	0.41*	0.49*	-0.21
afixa		0.61*	0.16	-0.12	0.41*	0.37*	0.09	0.22	0.16	0.06
afixc			0.16	-0.01	0.70*	0.43*	-0.05	0.26	0.28	0.07
afixh				-0.03	0.09	0.07	0.13	0.39*	0.28	-0.28
afixi					-0.17	0.51*	0	0.49*	0.2	-0.14
afixj						0.33	0.15	0.21	0.42*	0.28
afixk							0.19	0.72*	0.14	0.06
afixl								0.03	0.04	0.59*
afixm									0.3	-0.16
afixo										0.07

Table A-11: Regionally-averaged ensemble-mean change for the 2020s (relative to the 1980s) in drought intensity (*DI*), drought covariance index (*CI*), local drought covariance index (*LCI*), frequency of drought months (*FDM*) and frequency of drought events (*FDD*) with persistence of at least 3, 6, 8, 10 and 12 months under extreme droughts ($_{90}$) for 23 river basin regions. O&S refers to Orkney and Shetland; cardinal directions are abbreviated. Percentage change is shown for *DI* and *CI*, whereas absolute change (number of drought months and events per 30 year, respectively) is given for *FDM* and *FDD*. "-" denotes no data available.

	DI_{90}		CI_{90}		LCI_{90}		FDM_{90}		FDD_{90}				
	dry	wet	dry	wet	dry	wet	dry	wet	≥3	≥6	≥8	≥10	≥12
Anglian	-8.0	-4.6	12.7	-2.9	9.0	4.3	-0.4	0.9	0.3	0.3	0.1	-	-0.1
Humber	-12.2	-9.8	7.0	-5.2	7.2	-6.1	-2.1	-2.5	0.1	0.1	0.1	-	0.1
Northumbria	-19.9	-17.5	6.7	-5.2	10.1	-4.3	-4.9	-4.6	-0.6	-0.5	0.1	0.1	0.1
NW England	-12.3	-8.5	14.1	1.1	4.9	-3.8	-3.1	-3.1	-0.6	0.1	-	0.1	0.1
SE England	-6.6	-3.2	14.8	7.1	1.8	7.5	-1.8	0.9	0.2	0.3	-0.1	-0.2	-0.1
Severn	12.0	3.1	0.8	-2.1	5.0	0.8	2.3	2.6	0.3	0.3	0.3	0.1	0.2
SW England	5.8	2.1	8.5	3.7	3.3	0.5	0.8	3.4	0.5	0.2	0.1	-0.1	-0.1
Thames	1.1	1.0	7.2	1.4	3.7	8.8	0.3	2.7	0.4	0.4	0.1	-0.1	-0.1
Dee	16.0	7.0	-0.3	-1.8	1.2	-	3.9	5.2	0.1	0.4	0.4	0.5	0.3
W Wales	-0.3	-3.1	4.0	-0.2	4.4	-4.3	-1.2	-0.1	-0.3	0.2	0.1	0.1	0.2
Argyll	-17.1	-13.5	12.8	-4.1	-2.8	-3.5	-6.5	-5.4	-1.1	-0.6	-0.4	-0.1	-
Clyde	-21.8	-17.3	13.1	0.3	1.5	0.4	-5.8	-5.3	-0.9	-0.6	-0.1	0.1	0.1
Forth	-19.4	-16.1	11.9	-3.8	6.5	-5.5	-5.2	-5.1	-1.0	-0.7	-0.3	-	-
NE Scotland	-14.3	-10.2	5.4	-4.1	12.0	-4.4	-3.8	-2.7	-0.5	0.1	-	0.1	-
N Highland	-16.7	-12.4	11.2	5.6	15.9	6.2	-4.8	-3.3	-0.9	-0.3	-0.1	-	0.1
O&S	-3.4	-9.8	17.2	8.0	7.2	4.5	-3.2	-4.9	-0.2	0.1	0.2	-	-0.1
Solway	-17.5	-16.0	7.5	4.2	3.4	0.2	-4.3	-4.7	-1.0	-0.3	0.1	-	0.1
Tay	-11.0	-6.5	10.7	-7.3	6.2	-6.1	-2.2	-2.1	-0.6	-0.3	-	0.1	0.1
Tweed	-15.7	-15.5	-0.7	-1.3	7.7	-4.3	-2.3	-4.4	-0.1	-0.6	-0.1	-0.1	-
W Highland	-18.5	-15.8	17.6	14.1	8.4	13.2	-6.6	-3.5	-1.0	-0.8	-0.5	-0.3	-0.1
Neagh Bann	-4.9	-3.0	-6.1	-13.8	5.0	-10.3	-1.8	-2.0	-0.2	0.1	0.2	0.2	0.2
NE Ireland	-9.3	-3.6	-4.4	-8.1	6.4	-5.8	-1.9	-1.4	-0.7	-	-	0.1	0.1
NW Ireland	-5.7	-5.5	-0.8	-11.4	4.4	-2.2	-0.8	-1.3	-0.4	-0.2	0.1	0.2	0.1

Table A-12: As Table A-11, but for moderate ($_{70}$) droughts.

	DI_{70}		CI_{70}		LCI_{70}		FDM_{70}		FDD_{70}				
	dry	wet	dry	wet	dry	wet	dry	wet	≥3	≥6	≥8	≥10	≥12
Anglian	-7.3	1.1	5.3	2.4	3.2	-0.9	-3.1	3.9	0.1	-	0.2	-	-0.1
Humber	-18.0	-2.1	3.8	1.8	3.1	-0.4	-6.1	1.9	-0.3	-0.3	0.1	-	0.1
Northumbria	-29.3	-13.7	3.1	1.5	4.5	1.9	-9.2	-6.2	-1.2	-0.8	-0.5	-0.4	-0.1
NW England	-12.5	-6.0	6.6	1.4	4.9	1.2	-5.8	-5.3	-	-1.2	-0.5	-	0.1
SE England	-0.2	1.5	5.7	2.9	3.0	-1.5	0.5	2.1	0.4	-0.3	-	-	-0.1
Severn	9.1	5.2	3.2	0.5	5.1	0.1	3.8	4.4	0.8	0.1	0.3	0.2	0.1
SW England	11.5	5.6	5.2	3.1	3.2	-1.7	3.8	5.1	1.4	0.2	0.2	0.1	-
Thames	6.6	2.5	2.6	1.1	4.4	-0.4	2.0	3.6	0.6	0.3	0.4	0.1	-
Dee	20.5	10.6	3.2	-0.4	5.5	1.7	5.9	5.1	1.3	0.2	0.3	0.3	0.4
W Wales	3.0	-2.7	5.9	0.4	4.0	0.6	2.3	1.5	0.2	-1.0	-0.1	-	-
Argyll	-23.9	-27.8	8.0	4.3	3.1	0.5	-14.1	-10.7	-1.8	-1.5	-0.9	-0.7	-0.3
Clyde	-22.1	-16.4	6.3	3.7	2.0	-0.4	-10.7	-8.1	-2.0	-1.5	-1.3	-1.0	-0.6
Forth	-26.3	-17.9	5.6	2.0	4.1	0.5	-11.3	-7.7	-1.5	-1.3	-1.2	-0.4	-0.3
NE Scotland	-27.5	-20.7	2.6	-2.8	4.7	3.2	-11.0	-9.0	-1.5	-1.0	-0.3	-	0.1
N Highland	-27.6	-16.6	4.3	-	3.8	2.8	-12.0	-9.1	-1.8	-1.1	-0.5	-0.1	-0.1
O&S	5.9	-23.1	-0.4	-1.0	8.0	3.8	-1.6	-9.4	-1.1	-1.1	-	-0.1	0.1
Solway	-18.9	-13.6	8.1	0.5	4.4	0.7	-8.9	-6.9	-1.4	-1.6	-1.2	-0.8	-0.3
Tay	-18.8	-9.1	5.0	0.9	4.3	2.5	-8.8	-4.0	-1.1	-1.0	-0.6	-0.2	-0.1
Tweed	-27.1	-16.9	3.9	-2.1	4.3	0.2	-8.6	-7.8	-1.0	-0.8	-0.7	-0.3	-0.2
W Highland	-25.9	-29.5	9.8	-1.0	4.8	1.6	-13.7	-10.6	-1.9	-1.1	-1.0	-0.8	-0.4
Neagh Bann	-13.4	-3.2	3.7	-1.8	3.8	1.6	-5.0	-2.5	-	-0.8	-0.2	-0.1	-
NE Ireland	-18.0	-5.7	9.0	-0.9	4.1	0.6	-8.2	-3.7	-0.8	-1.2	-0.1	-0.3	-0.1
NW Ireland	-7.5	-2.8	-1.1	-1.7	4.1	1.2	-2.4	-1.8	0.1	-0.5	-1.0	-0.3	-

Table A-13: Regionally-averaged ensemble-mean change for the 2050s (relative to the 1980s) in drought intensity (*DI*), drought covariance index (*CI*), local drought covariance index (*LCI*), frequency of drought months (*FDM*) and frequency of drought events (*FDD*) with persistence of at least 3, 6, 8, 10 and 12 months under extreme droughts ($_{90}$) for 23 river basin regions. O&S refers to Orkney and Shetland; cardinal directions are abbreviated. Percentage change is shown for *DI* and *CI*, whereas absolute change (number of drought months and events per 30 year, respectively) is given for *FDM* and *FDD*. "-" denotes no data available.

	DI_{90}		CI_{90}		LCI_{90}		FDM_{90}		FDD_{90}				
	dry	wet	dry	wet	dry	wet	dry	wet	≥3	≥6	≥8	≥10	≥12
Anglian	2.0	11.0	12.9	4.7	9.1	6.6	1.4	10.6	0.8	0.2	0.3	0.1	0.1
Humber	-0.8	7.5	7.3	5.8	9.4	3.5	0.7	9.8	1.1	0.5	0.1	0.1	0.1
Northumbria	-10.8	1.4	7.7	9.1	10.7	9.3	-2.0	4.3	-0.1	-0.1	0.1	0.3	0.3
NW England	-14.1	0.5	26.5	10.6	11.3	9.0	-3.9	4.5	0.4	-	-0.1	-0.1	-
SE England	3.1	10.5	16.0	12.3	3.8	2.3	-0.1	8.7	1.2	0.2	-0.1	-0.2	-0.1
Severn	17.5	13.3	9.2	8.3	10.3	7.1	4.9	13.3	2.0	0.6	0.1	-	-
SW England	16.9	12.5	15.0	9.9	9.7	4.1	3.8	13.8	2.1	0.2	-0.1	-0.1	-
Thames	2.8	12.5	11.2	8.9	8.6	8.2	-	11.6	1.1	0.3	0.1	-0.1	-0.1
Dee	23.0	17.4	13.1	6.8	9.6	6.8	5.7	15.7	2.6	1.1	0.1	0.1	0.1
W Wales	8.0	9.5	13.2	6.4	12.2	7.9	2.9	10.2	1.6	0.4	0.2	0.1	-
Argyll	-28.2	-21.8	12.8	-7.7	7.4	2.5	-7.8	-7.6	-1.3	-0.8	-0.5	-0.2	-0.1
Clyde	-26.8	-13.5	23.7	9.0	10.1	8.2	-6.5	-3.5	-0.7	-0.6	-	0.2	-
Forth	-20.6	-7.3	21.4	8.5	11.9	8.0	-4.9	-1.2	-0.4	-0.5	-0.3	0.1	0.2
NE Scotland	-9.1	13.0	9.3	12.0	18.7	13.6	-2.6	5.1	0.5	0.3	0.5	0.3	0.1
N Highland	-14.9	-2.2	24.8	21.8	28.0	14.9	-4.9	-0.3	-0.3	-	0.2	0.1	0.1
O&S	-17.4	-16.2	15.4	27.4	20.3	11.7	-7.0	-7.7	-0.4	-0.3	0.2	0.1	-
Solway	-18.5	-10.6	19.1	6.5	12.6	9.7	-4.6	-1.5	-0.2	0.1	0.1	-	-
Tay	-16.7	6.1	18.1	7.3	11.7	10.3	-2.2	3.5	0.3	-	0.3	0.2	0.2
Tweed	-11.5	-5.6	15.2	11.5	10.7	7.5	-2.0	2.9	-0.1	-0.3	-	0.1	0.2
W Highland	-30.1	-24.7	26.9	9.8	17.7	6.5	-8.3	-6.8	-1.1	-0.9	-0.6	-0.4	-0.1
Neagh Bann	-5.6	10.1	-0.2	-2.5	13.1	8.5	-0.2	6.7	0.4	0.3	0.1	0.2	0.3
NE Ireland	-0.9	7.7	-13.0	-2.1	15.7	1-	0.6	4.1	-0.1	0.4	0.3	0.2	0.3
NW Ireland	-12.5	3.2	11.3	2.9	9.5	8.0	-2.7	4.2	0.4	-	0.4	0.3	0.3

Table A-14: As Table A-13, but for moderate ($_{70}$) droughts.

	DI_{70}		CI_{70}		LCI_{70}		FDM_{70}		FDD_{70}				
	Dry	wet	dry	wet	dry	wet	dry	wet	≥3	≥6	≥8	≥10	≥12
Anglian	14.5	33.8	9.9	3.7	5.9	2.1	4.7	18.9	2.5	1.0	-	-	0.1
Humber	-0.9	26.6	7.3	2.4	6.4	2.0	0.9	12.8	2.8	1.1	-0.1	-0.3	-
Northumbria	-11.1	15.0	7.1	3.8	9.6	4.2	-5.1	9.5	1.5	0.5	-0.3	-0.3	-0.1
NW England	-8.5	7.9	12.7	4.1	8.9	2.2	-5.6	4.5	2.4	-0.6	-1.0	-0.8	-0.5
SE England	16.0	16.7	8.4	7.2	7.4	2.0	6.4	9.7	3.5	0.3	-0.3	-0.4	-0.3
Severn	27.8	24.8	6.9	4.0	8.8	2.4	9.3	14.0	4.3	1.6	0.4	-0.2	-0.2
SW England	28.4	20.7	7.1	6.5	7.7	1.8	10.3	12.3	4.9	1.3	0.1	-0.3	-0.2
Thames	20.3	26.9	7.8	6.4	7.6	2.4	6.7	17.1	3.9	1.1	-	-0.1	-0.3
Dee	38.5	25.8	6.9	1.2	11.0	4.3	10.8	14.8	4.3	1.8	0.4	-	-
W Wales	12.6	15.1	9.2	2.6	8.8	2.6	6.0	6.3	3.5	-0.2	-0.1	-	-
Argyll	-35.3	-42.2	16.8	3.7	9.3	3.2	-20.1	-14.2	-2.4	-1.8	-1.3	-0.9	-0.5
Clyde	-21.8	-8.6	16.0	5.5	7.7	2.4	-11.1	-6.7	-1.3	-1.6	-1.2	-0.9	-0.8
Forth	-24.4	-5.7	11.0	4.4	8.5	3.7	-10.6	-0.5	0.3	-0.9	-1.0	-0.6	-0.4
NE Scotland	-17.4	-1.5	8.2	2.0	12.2	5.8	-10.3	2.0	0.5	-0.1	-	0.3	-
N Highland	-22.7	-11.8	11.1	1.1	13.0	5.4	-10.4	-3.4	-1.0	-0.7	-0.5	-	-
O&S	-22.1	-29.8	3.5	5.3	14.6	5.1	-10.7	-14.4	-1.6	-1.5	-1.6	-0.6	-0.1
Solway	-15.7	-0.9	14.2	5.4	8.7	2.3	-8.0	1.3	0.2	-1.1	-1.0	-0.8	-0.3
Tay	-18.4	9.7	10.9	3.9	10.0	4.7	-2.6	6.1	1.8	-0.3	-0.3	-0.1	-
Tweed	-13.1	5.4	7.4	2.5	9.1	3.4	-5.6	2.9	1.4	-0.3	-0.7	-0.5	-0.1
W Highland	-34.9	-43.1	18.7	1.3	11.4	3.5	-19.2	-15.3	-2.6	-1.8	-1.4	-0.9	-0.7
Neagh Bann	-5.0	20.2	10.2	0.9	9.5	4.4	-4.5	7.1	1.5	-	-0.1	-0.1	0.2
NE Ireland	-8.4	23.0	14.3	1.6	9.6	4.3	-4.3	9.3	1.5	0.1	-0.1	0.1	0.4
NW Ireland	-7.7	14.5	7.9	1.5	9.0	3.5	-1.3	5.8	1.7	-0.4	-0.9	-0.3	0.3

Table A-15: Proportion of the UK domain represented by a given percentage change in ensemble-mean drought intensity (*DI*) for extreme ($_{90}$) and moderate ($_{70}$) droughts and for the wet (^{wet}) and dry (^{dry}) seasons, relative to 1980s. The different levels of consensus across ensemble members are represented by C_n (no consensus), C_m (moderate consensus) and C_h (high consensus). "-" reflects either no change or no data available.

Aspect	Period	≤ -25	≤ -20	≤ -15	≤ -10	≤ -5	≤ 0	≥ 0	≥ 5	≥ 10	≥ 15	≥ 20	C_n	C_m	C_h
DI_{90}^{dry}	2020s	3.7	14.3	27.2	36.9	45.8	50.9	12.2	8.6	4.3	1.6	0.5	0.3	36.9	41.7
	2050s	9.5	15.6	22.4	29.3	32.4	38.0	22.1	15.3	11.3	7.3	4.6	2.1	39.9	41.8
	2080s	10.0	17.2	26.2	33.1	38.2	43.9	29.7	22.6	14.5	8.6	4.8	2.1	26.4	45.3
DI_{70}^{dry}	2020s	18.8	29.1	36.9	41.3	47.4	51.4	11.8	9.5	5.4	3.0	1.1	0.6	36.9	41.7
	2050s	12.7	16.9	22.4	27.0	32.0	36.3	23.9	21.0	19.7	17.7	13.5	8.4	39.9	41.8
	2080s	17.7	21.1	26.6	32.3	36.7	39.4	34.2	31.0	28.3	24.5	18.4	12.6	26.4	45.3
DI_{90}^{wet}	2020s	1.6	5.7	18.1	30.8	44.5	57.1	14.5	2.7	1.0	-	-	-	28.5	59.3
	2050s	4.5	6.2	9.4	13.7	18.6	23.4	58.2	53.3	33.9	11.5	3.5	1.6	18.4	40.2
	2080s	4.3	6.5	9.9	16.9	22.1	26.4	57.4	51.8	35.1	14.8	4.8	1.3	16.2	34.2
DI_{70}^{wet}	2020s	8.9	13.2	18.8	28.3	39.8	49.0	22.6	8.9	0.8	-	-	-	28.5	59.3
	2050s	7.5	8.9	10.2	13.7	16.5	18.8	62.8	59.3	55.5	49.9	40.7	26.6	18.4	40.2
	2080s	10.3	12.9	15.7	19.6	22.9	26.9	56.9	54.5	53.4	48.8	44.5	32.6	16.2	34.2

Table A-16: As Table A-15, but for drought covariance index (*CI*).

Aspect	Period	≤ -25	≤ -20	≤ -15	≤ -10	≤ -5	≤ 0	≥ 0	≥ 5	≥ 10	≥ 15	≥ 20	C_n	C_m	C_h
CI_{90}^{dry}	2020s	-	0.2	0.8	4.9	11.0	43.1	35.5	24.0	13.7	6.0	1.9	46.0	46.1	7.9
	2050s	-	0.5	1.3	3.2	5.3	66.3	61.8	50.4	35.0	20.2	12.1	28.5	52.3	19.2
	2080s	0.3	0.5	0.6	1.1	1.9	81.2	77.3	67.6	52.9	38.8	26.1	16.9	45.9	37.2
CI_{70}^{dry}	2020s	-	-	-	-	4.5	63.8	34.2	5.6	0.3	-	-	31.8	46.7	21.5
	2050s	-	-	-	-	-	96.3	88.4	38.6	12.2	4.0	0.5	3.7	28.9	67.4
	2080s	-	-	-	0.2	0.5	94.9	91.7	50.6	17.8	5.6	0.8	4.6	20.8	74.6
CI_{90}^{wet}	2020s	-	1.3	5.7	17.3	29.6	17.7	10.5	5.1	2.2	0.5	-	52.8	44.5	2.7
	2050s	-	0.3	1.1	2.2	7.5	55.0	44.2	25.6	9.5	4.8	2.5	37.5	54.1	8.4
	2080s	0.2	0.2	0.6	1.1	2.7	69.5	61.4	45.5	25.6	11.1	4.8	27.8	51.2	21.0
CI_{70}^{wet}	2020s	-	-	-	1.8	18.1	36.1	4.0	-	-	-	-	45.8	49.1	5.1
	2050s	-	-	0.2	1.0	6.2	64.9	26.6	0.6	-	-	-	28.9	47.1	24.0
	2080s	-	-	-	1.0	3.0	74.2	40.4	5.6	-	-	-	22.7	47.7	29.6

Table A-17: As Table A-15, but for local drought covariance index (*LCI*).

Aspect	Period	≤ -25	≤ -20	≤ -15	≤ -10	≤ -5	≤ 0	≥ 0	≥ 5	≥ 10	≥ 15	≥ 20	C_n	C_m	C_h
	2020s	-	0.3	1.9	7.0	41.3	32.1	13.7	4.6	0.8	0.2	51.7	46.1	4.0	-
LCI_{90}^{dry}	2050s	-	-	-	1.1	67.1	61.4	42.3	16.7	8.6	6.0	31.8	52.3	13.2	-
	2080s	-	-	-	0.2	89.2	87.9	74.2	45.3	19.6	6.2	10.7	45.9	37.8	-
	2020s	-	-	-	-	85.1	22.4	-	-	-	-	14.9	46.7	28.8	-
LCI_{70}^{dry}	2050s	-	-	-	-	99.7	96.0	26.9	1.9	-	-	0.3	28.9	91.6	-
	2080s	-	-	-	-	100.0	99.5	45.2	5.1	0.2	-	-	20.8	99.2	-
	2020s	0.3	3.8	15.9	29.4	21.5	13.2	4.8	1.3	-	-	49.1	44.5	5.4	0.3
LCI_{90}^{wet}	2050s	-	0.2	0.6	3.7	58.2	47.7	21.8	6.5	0.8	-	38.2	54.1	11.4	-
	2080s	-	-	-	0.5	73.5	69.3	41.5	13.2	3.0	0.5	26.1	51.2	19.1	-
	2020s	-	-	-	15.6	33.7	1.0	-	-	-	-	50.7	49.1	5.4	-
LCI_{70}^{wet}	2050s	-	-	-	0.8	74.7	9.4	-	-	-	-	24.5	47.1	24.3	-
	2080s	-	-	-	-	87.9	26.4	0.8	-	-	-	12.1	47.7	45.6	-

Table A-18: As Table A-15, but for frequency of drought months (*FDM*) with figures showing absolute change (expressed as number of drought months per 30-year).

Aspect	Period	≤ -25	≤ -20	≤ -15	≤ -10	≤ -5	≤ 0	≥ 0	≥ 5	≥ 10	≥ 15	≥ 20	C_n	C_m	C_h
	2020s	-	-	-	-	16.4	41.8	13.8	0.5	-	-	-	44.4	42.9	11.9
FDM_{90}^{dry}	2050s	-	-	-	2.7	17.5	39.0	23.2	5.6	-	-	-	37.8	43.1	18.4
	2080s	-	-	-	2.5	20.5	42.0	25.8	6.5	0.6	-	-	32.3	44.2	22.4
	2020s	-	0.8	6.7	21.0	40.2	51.0	18.3	3.3	-	-	-	30.7	46.7	22.4
FDM_{70}^{dry}	2050s	2.1	4.6	8.0	15.9	23.7	30.5	35.0	27.2	7.8	0.2	-	34.5	41.8	23.5
	2080s	1.4	3.3	9.2	17.2	25.9	30.5	46.4	30.4	8.4	0.6	-	23.1	43.4	33.1
	2020s	-	-	-	-	11.5	39.8	22.4	2.7	-	-	-	37.8	53.6	7.9
FDM_{90}^{wet}	2050s	-	-	-	0.3	7.8	20.2	61.2	54.2	33.7	6.0	0.3	18.6	42.9	38.5
	2080s	-	-	-	2.2	8.4	19.9	63.9	55.3	37.8	12.2	1.9	16.2	39.1	44.0
	2020s	-	-	0.8	9.7	26.4	39.9	34.7	11.1	-	-	-	25.4	58.5	15.9
FDM_{70}^{wet}	2050s	-	1.6	4.5	7.3	11.6	15.1	68.7	60.4	43.2	22.7	5.3	16.2	35.3	48.5
	2080s	1.1	2.7	5.7	9.9	16.7	21.5	58.5	52.8	42.5	20.0	2.7	20.0	32.3	47.1

Table A-19: Proportion of UK domain represented by a given change factor (expressed as number of events per 30-year period) in ensemble-mean frequency of drought events (*FDD*) with persistence of at least 3, 6, 10 and 12 months under moderate ($_{70}$) drought conditions, relative to the 1980s. The different levels of consensus across ensemble members are represented by C_n (no consensus), C_m (moderate consensus) and C_h (high consensus). "-" reflects either no change or no data available.

Aspect	Period	≤ -4	≤ -3	≤ -2	≤ -1	≤ 0	≥ 0	≥ 1	≥ 2	≥ 3	≥ 4	≥ 5	C_n	C_m	C_h
FDD_{70} ≥3	2020s	-	-	7.6	23.2	35.0	27.0	8.0	1.3	-	-	-	38.0	48.2	11.6
	2050s	0.3	2.7	7.3	11.8	14.3	67.6	63.0	51.4	34.2	17.5	4.5	18.1	34.2	47.4
	2080s	0.2	2.1	4.8	7.3	9.7	77.6	70.1	59.6	44.8	25.0	11.0	12.7	30.0	56.3
FDD_{70} ≥6	2020s	-	-	0.8	23.7	44.4	18.6	0.5	-	-	-	-	37.0	52.5	7.0
	2050s	-	-	5.3	17.5	28.5	45.6	24.5	3.7	-	-	-	25.9	50.6	22.1
	2080s	-	0.2	3.7	16.9	29.7	47.2	19.4	2.7	-	-	-	23.1	51.7	24.2
FDD_{70} ≥10	2020s	-	-	-	2.4	30.5	35.8	-	-	-	-	-	33.7	51.8	11.4
	2050s	-	-	-	5.3	39.0	19.6	0.2	-	-	-	-	41.5	49.1	6.0
	2080s	-	-	-	12.4	47.2	14.3	0.6	-	-	-	-	38.5	47.2	13.5
FDD_{70} ≥12	2020s	-	-	-	-	32.9	37.0	-	-	-	-	-	30.1	55.2	13.4
	2050s	-	-	-	0.8	32.9	27.3	-	-	-	-	-	39.8	49.3	7.5
	2080s	-	-	-	2.7	44.2	22.3	0.2	-	-	-	-	33.6	51.8	13.8

Table A-20: As Table A-19, but for extreme ($_{90}$) drought conditions.

Aspect	Period	≤ -2	≤ -1	≤ 0	≥ 0	≥ 1	≥ 2	≥ 3	≥ 4	C_n	C_m	C_h
FDD_{90} ≥3	2020s	-	9.7	32.9	34.0	1.9	-	-	-	33.1	54.5	8.7
	2050s	-	6.5	21.1	53.1	33.6	10.5	2.1	0.3	25.8	49.4	23.7
	2080s	0.2	8.1	21.5	56.0	36.7	9.1	1.0	-	22.6	52.6	23.2
FDD_{90} ≥6	2020s	-	0.3	21.5	45.2	0.3	-	-	-	33.4	52.3	11.4
	2050s	-	1.8	22.4	48.5	3.3	-	-	-	29.1	55.0	12.1
	2080s	-	4.1	27.5	49.4	4.3	-	-	-	23.1	55.3	18.9
FDD_{90} ≥10	2020s	-	-	31.0	49.9	-	-	-	-	19.1	45.2	35.3
	2050s	-	-	30.2	53.1	-	-	-	-	16.7	52.3	29.7
	2080s	-	-	40.9	35.6	0.2	-	-	-	23.5	44.7	30.5
FDD_{90} ≥12	2020s	-	-	32.6	60.1	-	-	-	-	7.3	28.9	63.8
	2050s	-	-	31.3	63.3	-	-	-	-	5.4	34.8	59.1
	2080s	-	-	46.1	47.4	-	-	-	-	6.5	31.6	61.5

Appendix B – List *of* Figures

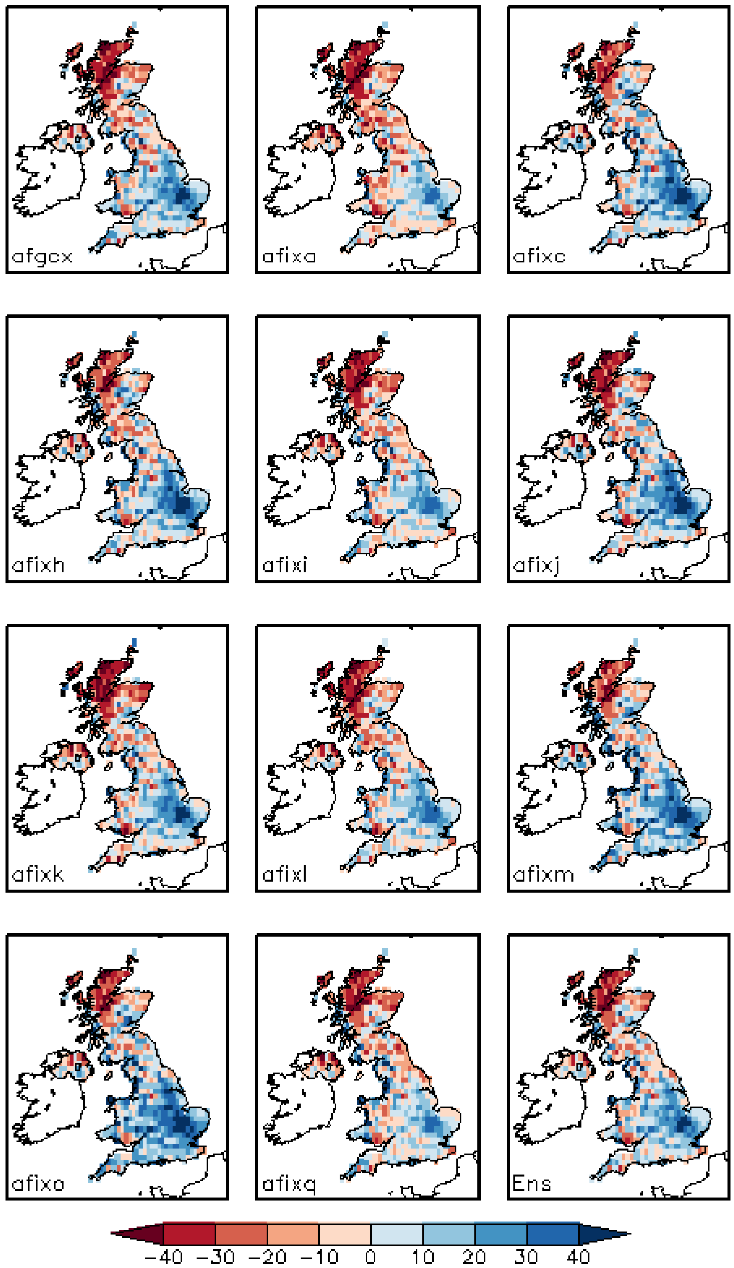

Figure A-1: Bias in mean seasonal rainfall (*msRAIN*) during the wet season for each of the 11-member ensemble (afgcx to afixq). Color bar shows the percentage change relative to the observed data. Ens refers to the ensemble mean bias.

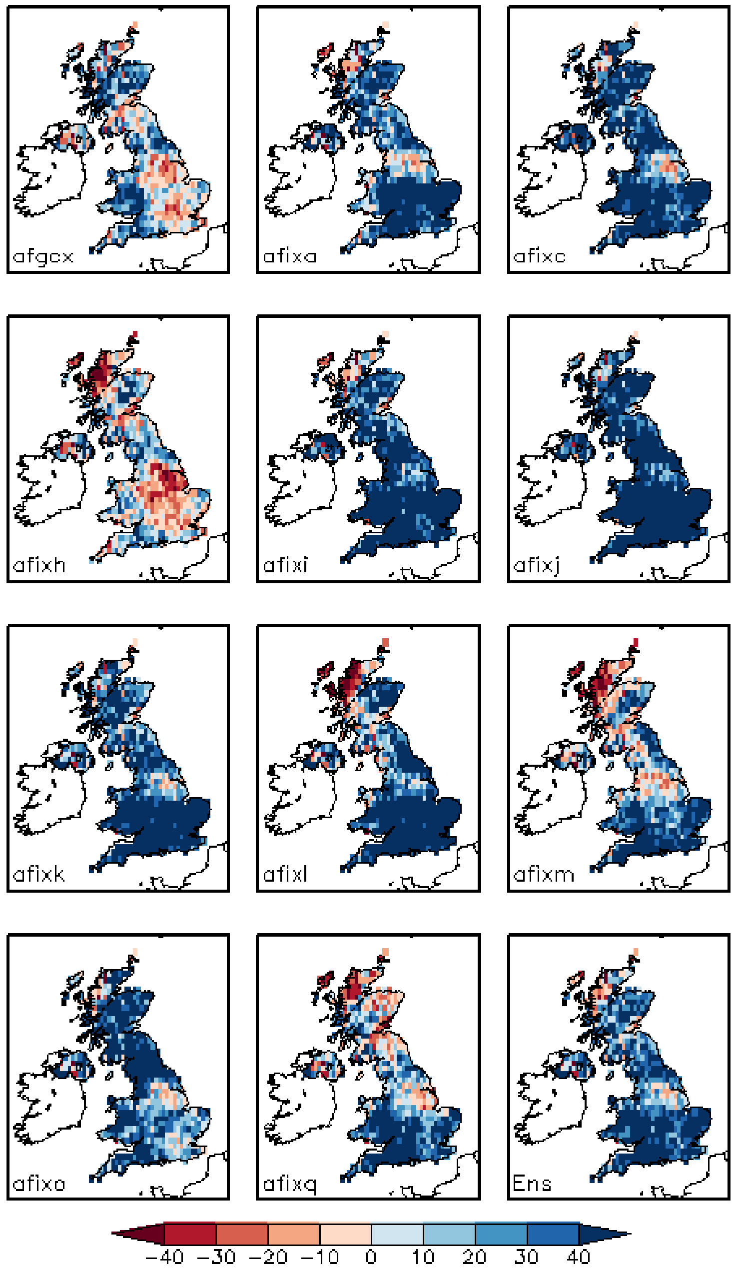

Figure A-2: Bias in mean seasonal DSI6 (*msDSI6*) during the wet season for each of the 11-member ensemble (afgcx to afixq). Color bar shows the percentage change relative to the observed data. Ens refers to the ensemble mean bias.

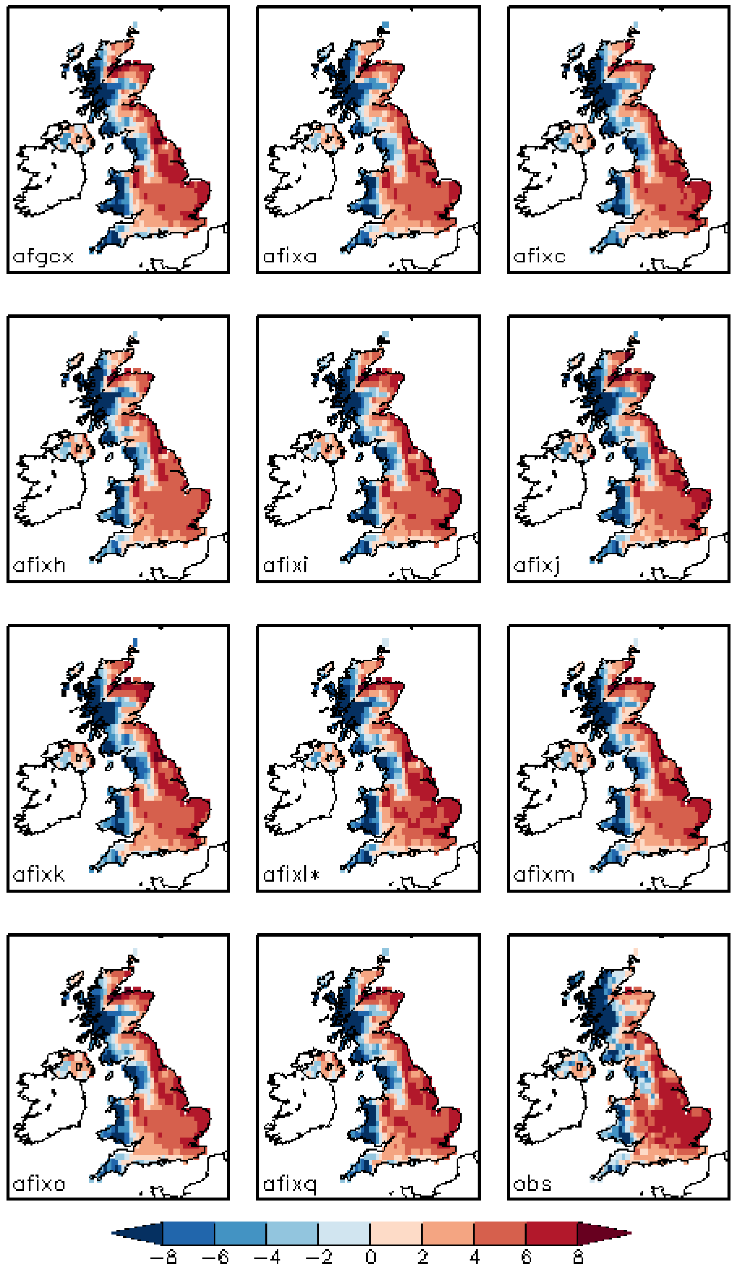

Figure A-3: Spatial patterns of principal component 1 (PC 1) for mean seasonal rainfall (*msRAIN*) during the wet season for each of the 11-member ensemble (afgcx to afixq) and the observed (obs) data. * indicates that the sign of the principal component has been reversed.

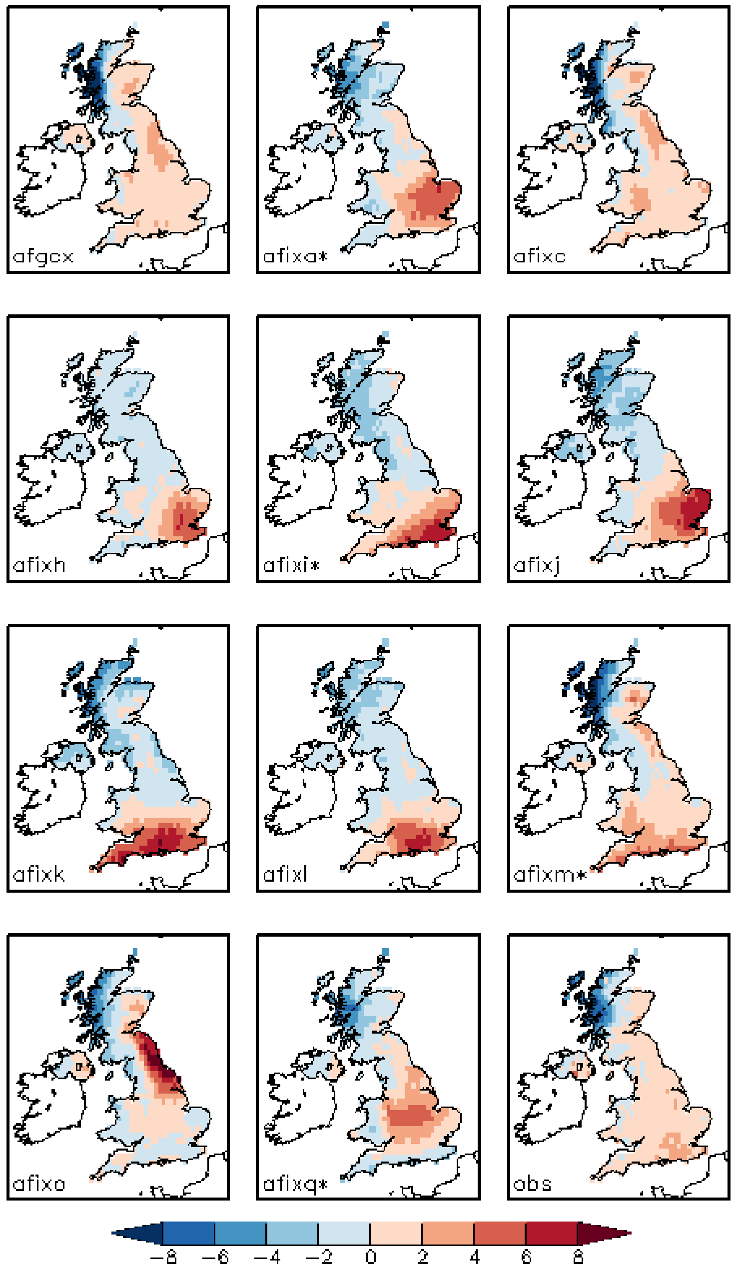

Figure A-4: Spatial patterns of principal component 1 (PC 1) for mean seasonal DSI6 (*msDSI6*) during the wet season for each of the 11-member ensemble (afgcx to afixq) and the observed (obs) data. * indicates that the sign of the principal component has been reversed.

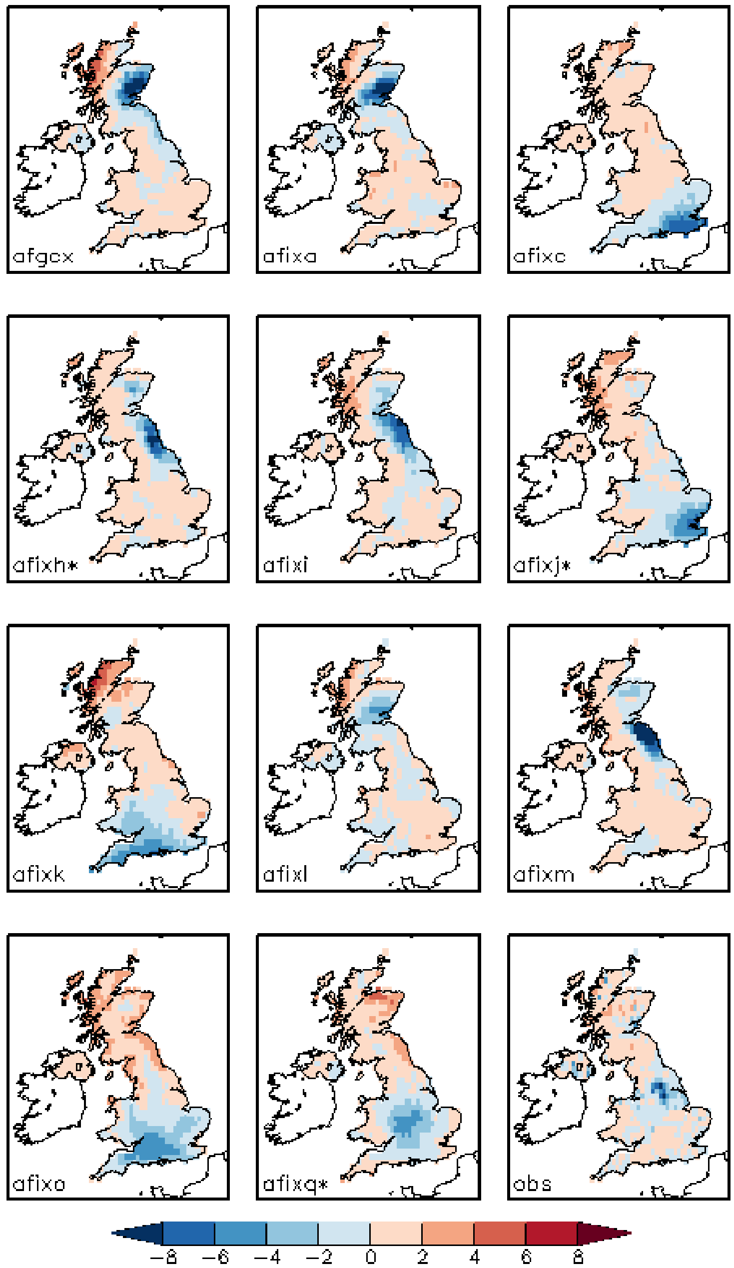

Figure A-5: Spatial patterns of principal component 2 (PC 2) for mean seasonal DSI6 (*msDSI6*) during the dry season for each of the 11-member ensemble (afgcx to afixq) and the observed (obs) data. * indicates that the sign of the principal component has been reversed.

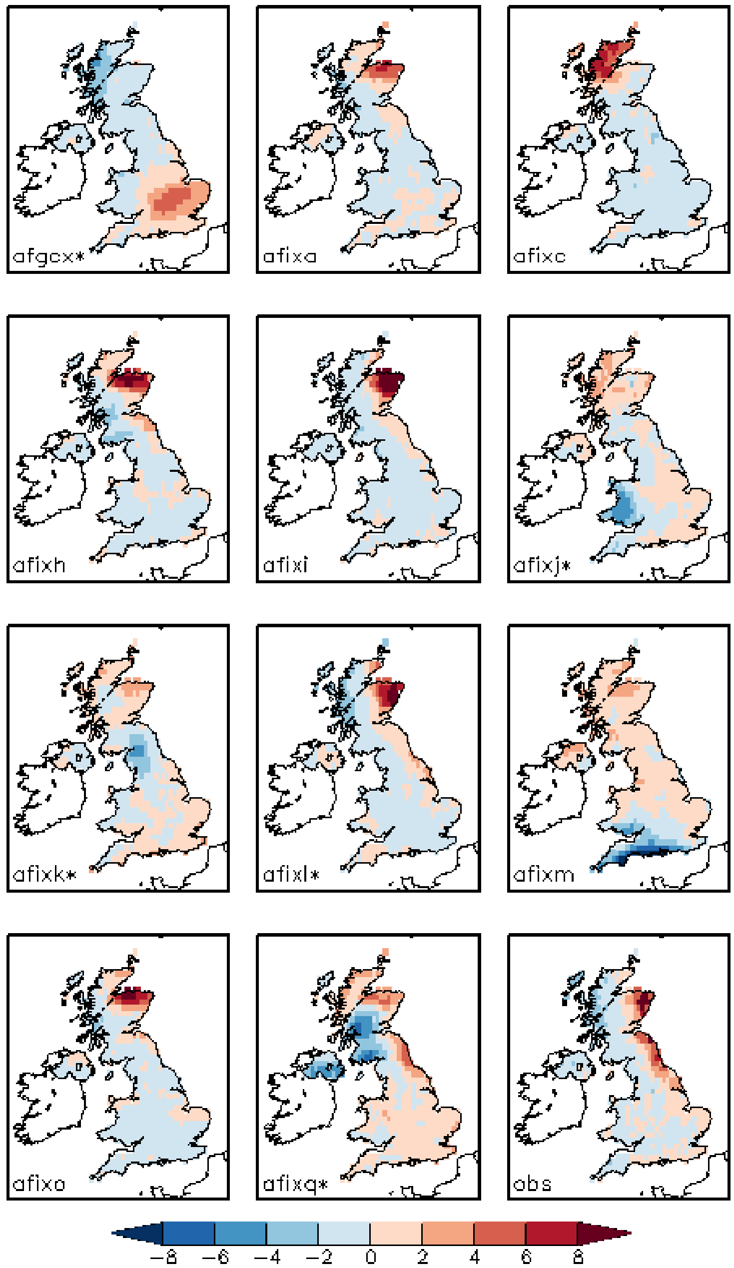

Figure A-6: As Figure A-5, but for PC 3.

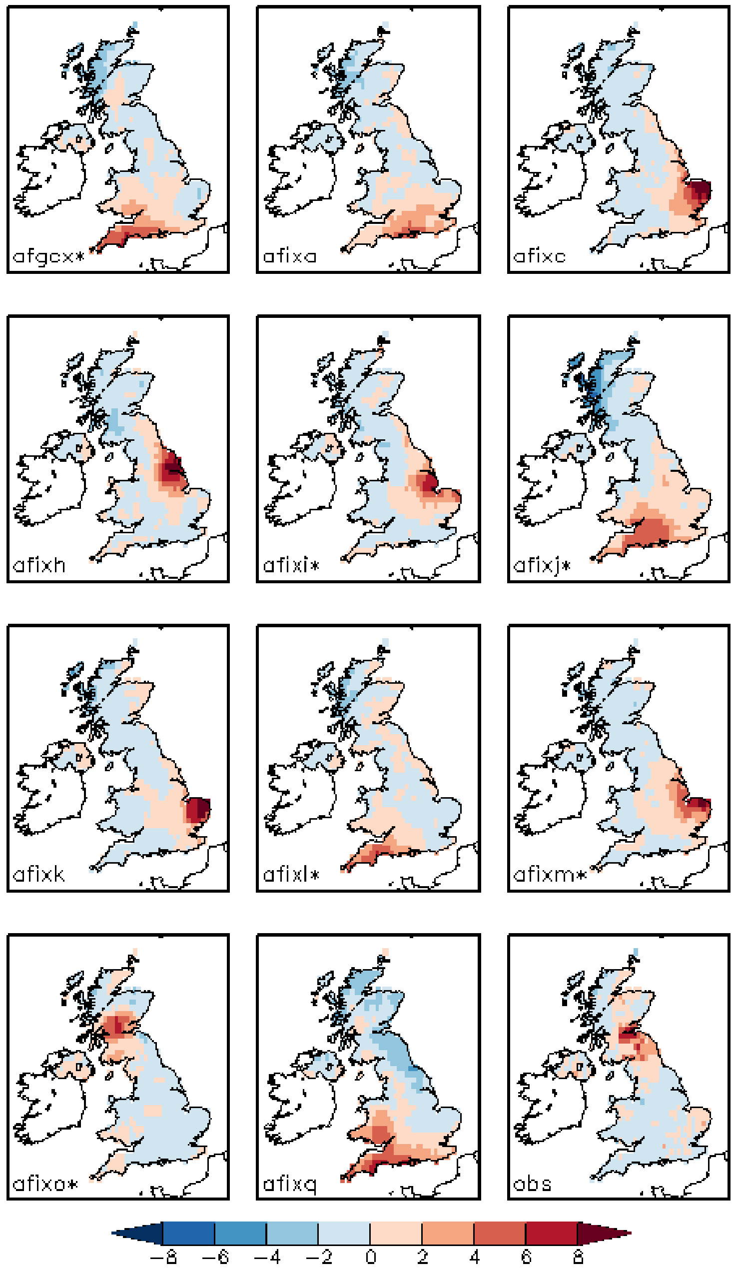

Figure A-7: As Figure A-5, but for PC 4.

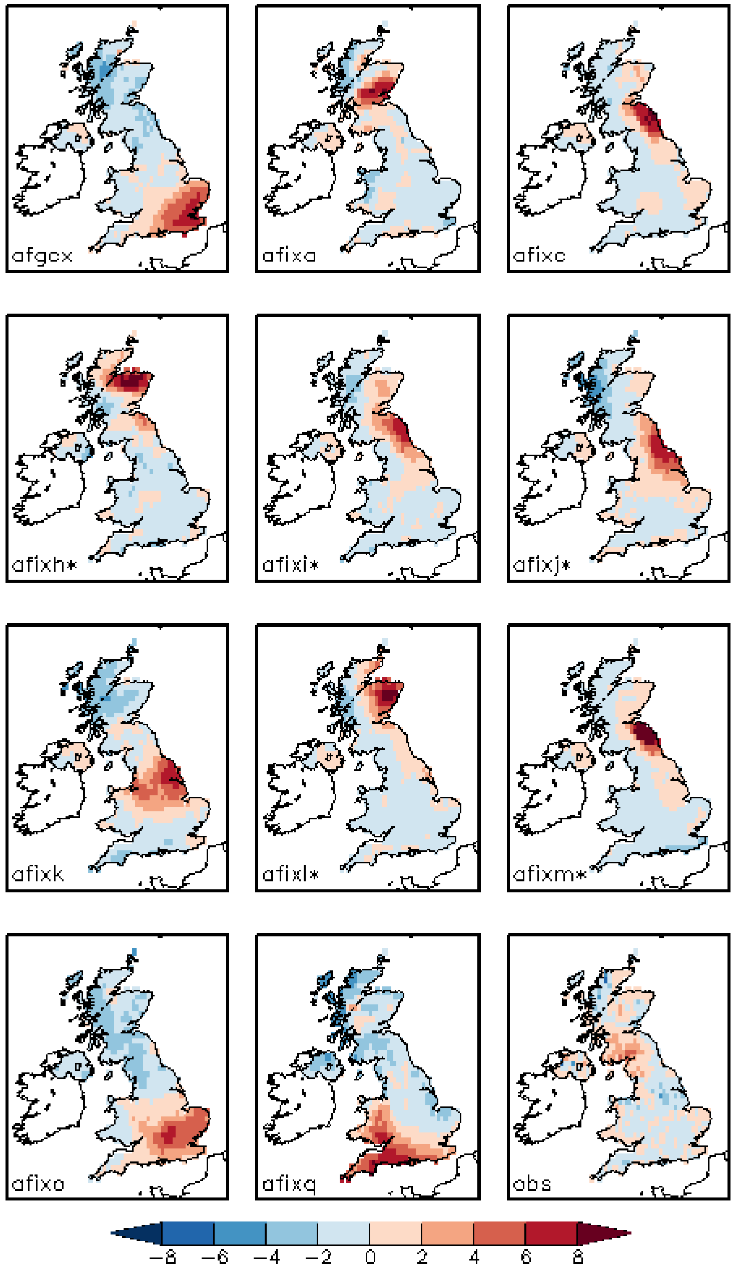

Figure A-8: Spatial patterns of principal component 2 (PC 2) for mean seasonal DSI6 (*msDSI6*) during the wet season for each of the 11-member ensemble (afgcx to afixq) and the observed (obs) data. * indicates that the sign of the principal component has been reversed.

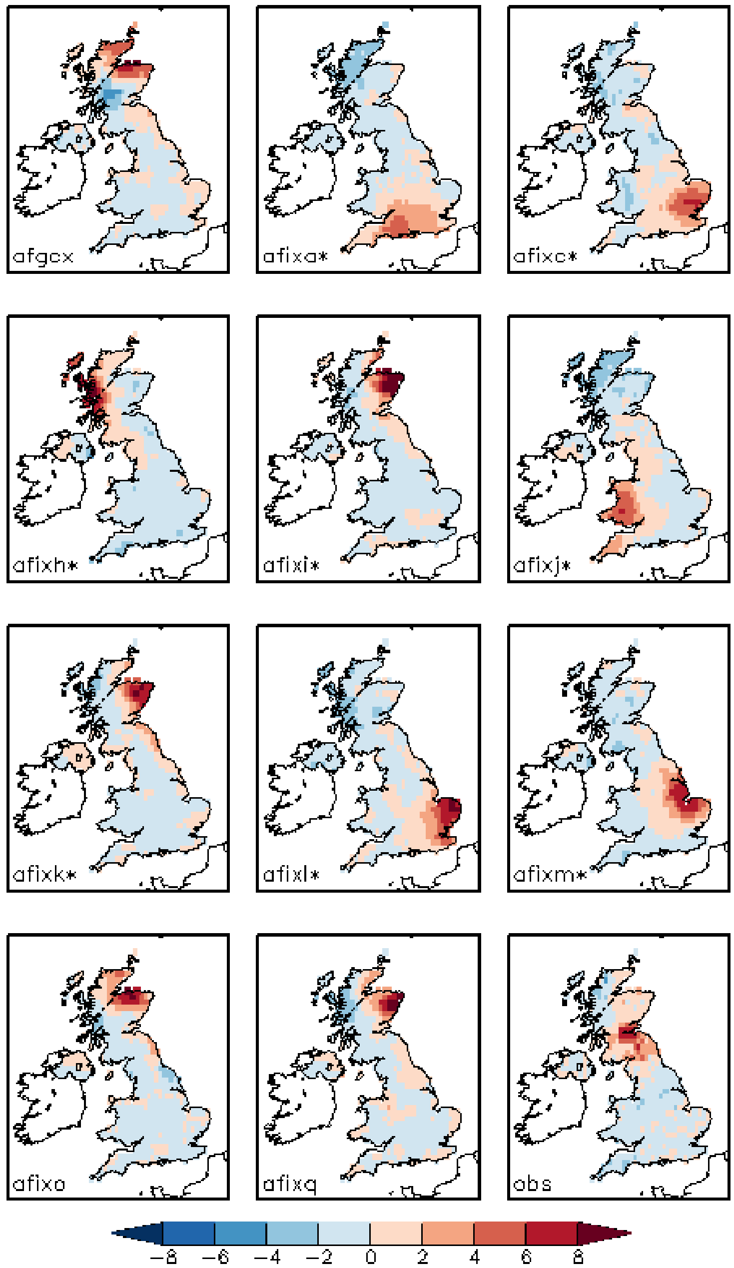

Figure A-9: As Figure A-8, but for PC 3

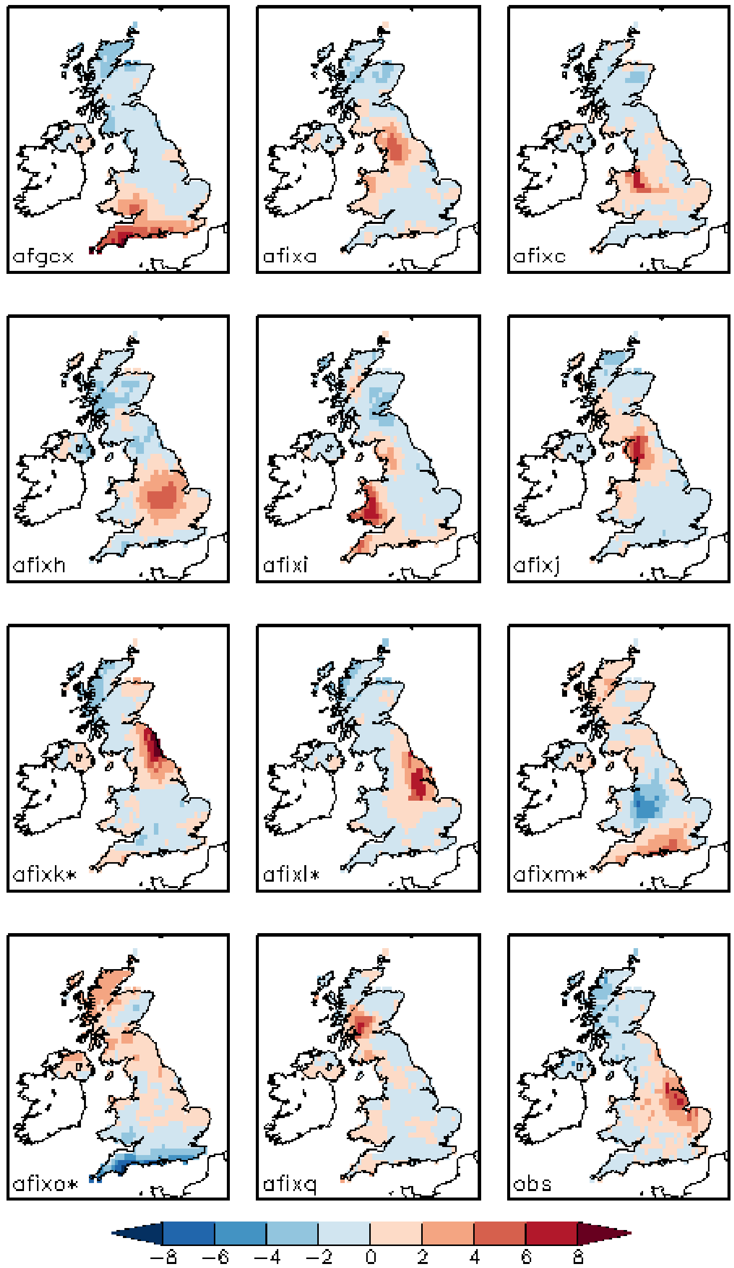

Figure A-10: As Figure A-8, but for PC 4

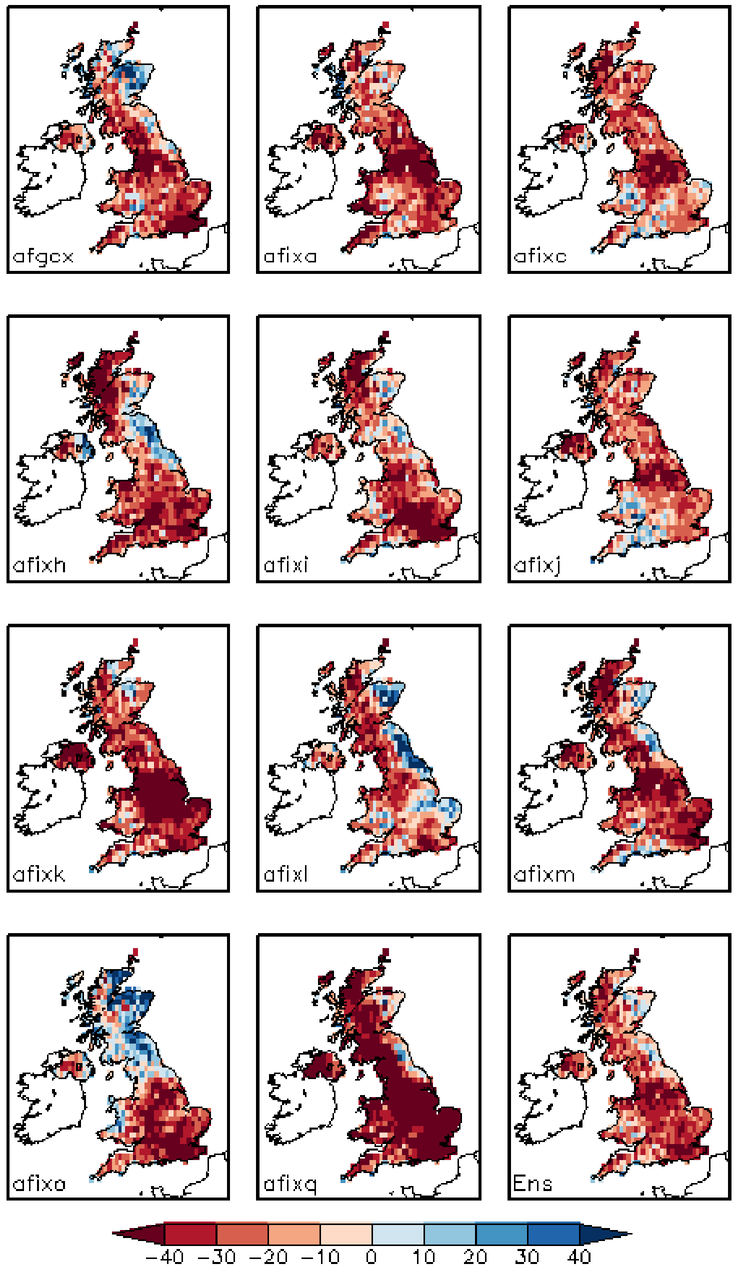

Figure A-11: Bias in drought intensity (*DI*) during the dry season under moderate drought conditions for each of the 11-member ensemble (afgcx to afixq). Color bar shows the percentage change relative to the observed data. Ens refers to the ensemble mean bias.

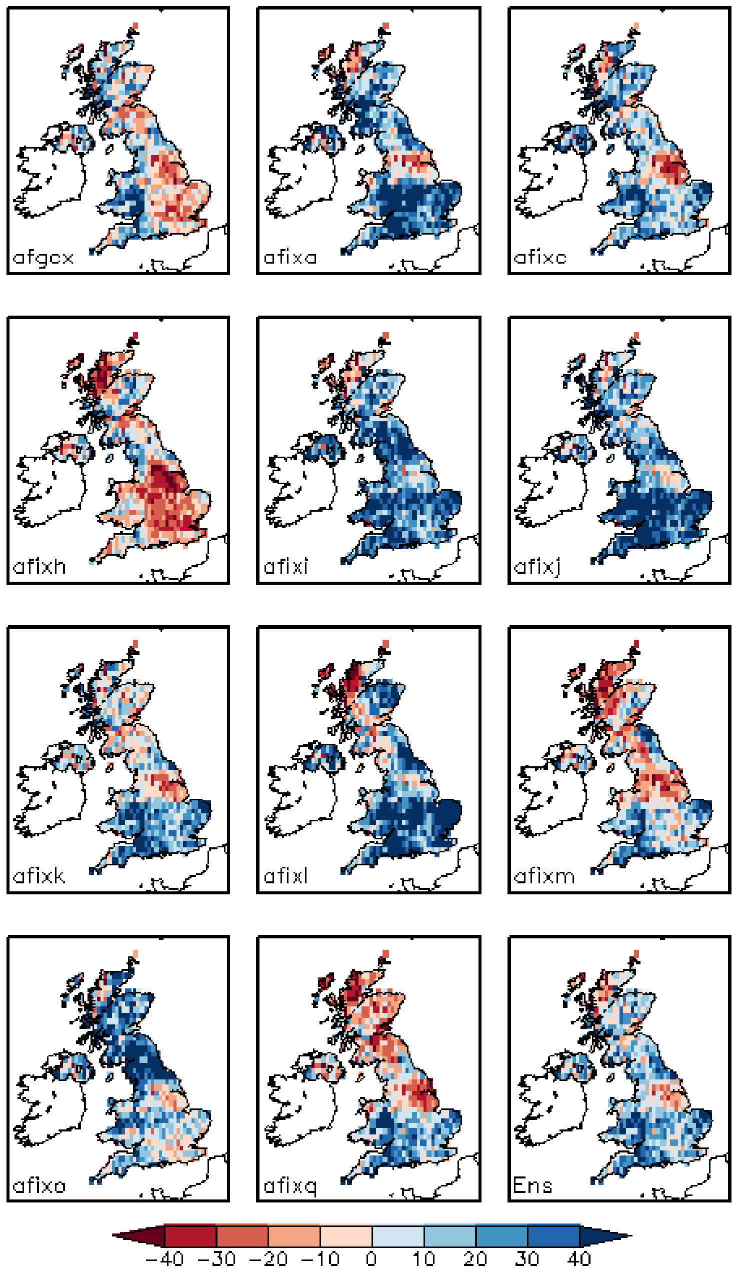

Figure A-12: Bias in drought intensity (*DI*) during the wet season under extreme drought conditions for each of the 11-member ensemble (afgcx to afixq). Color bar shows the percentage change relative to the observed data. Ens refers to the ensemble mean bias.

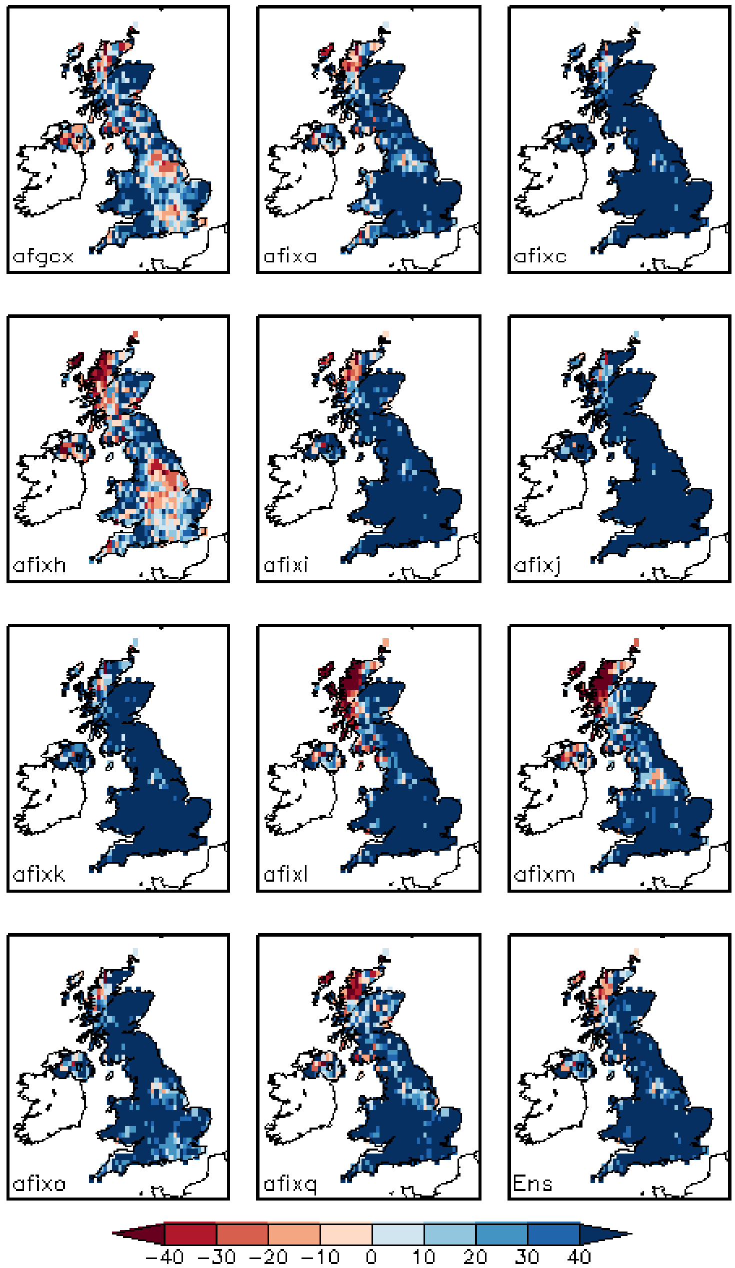

Figure A-13: Bias in drought intensity (*DI*) during the wet season under moderate drought conditions for each of the 11-member ensemble (afgcx to afixq). Color bar shows the percentage change relative to the observed data. Ens refers to the ensemble mean bias.

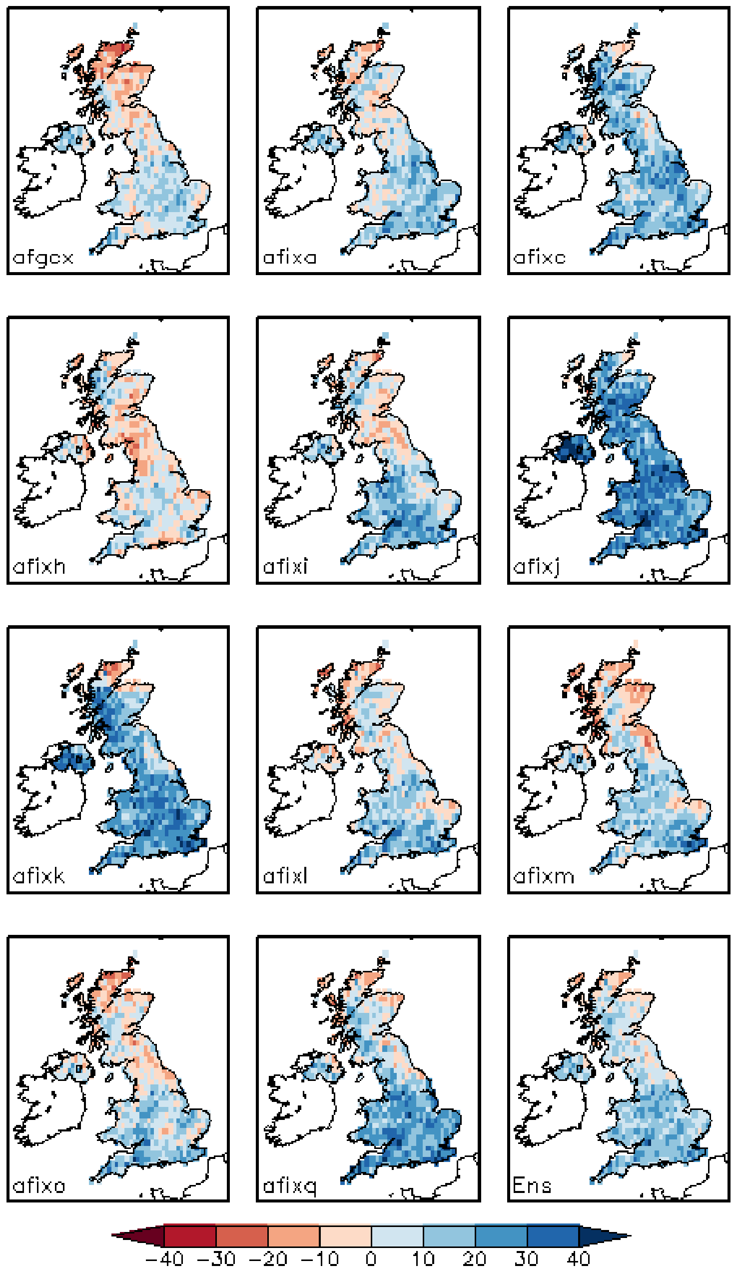

Figure A-14: Bias in drought covariance index (*CI*) during the dry season under moderate drought conditions for each of the 11-member ensemble (afgcx to afixq). Color bar shows the percentage change relative to the observed data. Ens refers to the ensemble mean bias.

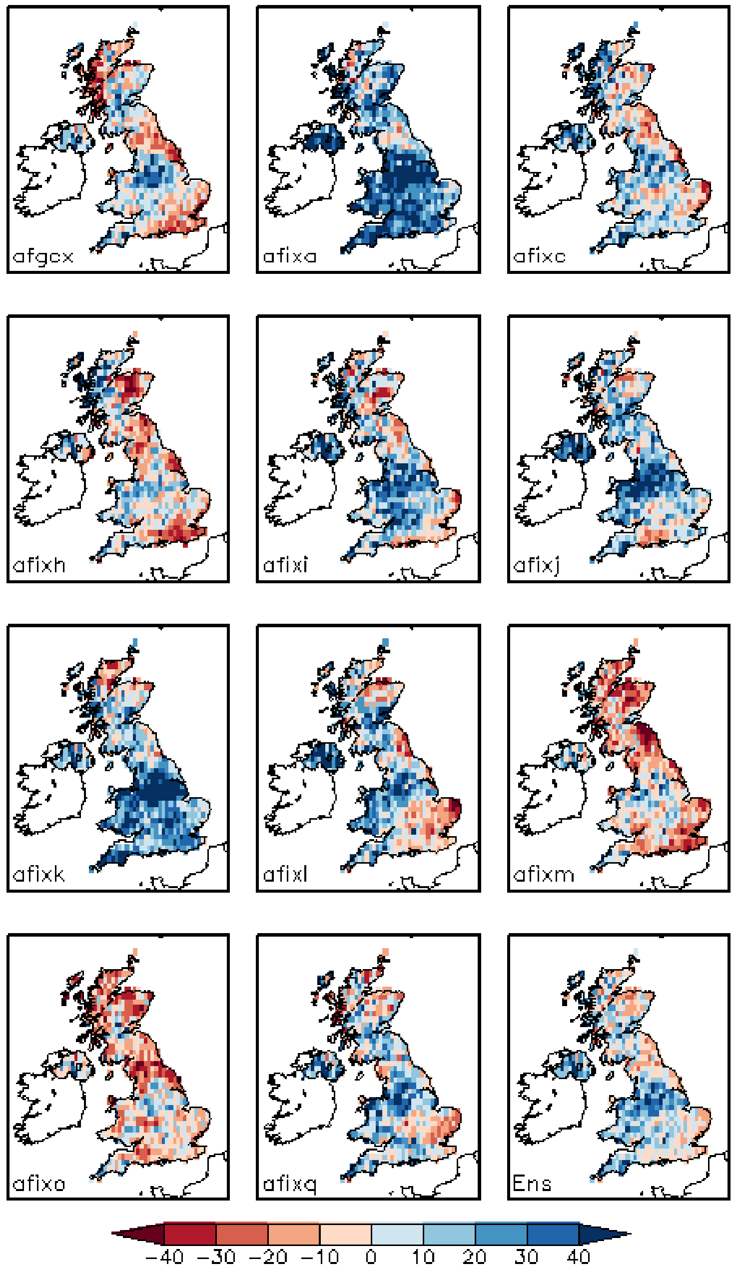

Figure A-15: Bias in drought covariance index (*CI*) during the wet season under extreme drought conditions for each of the 11-member ensemble (afgcx to afixq). Color bar shows the percentage change relative to the observed data. *Ens* refers to the ensemble mean bias.

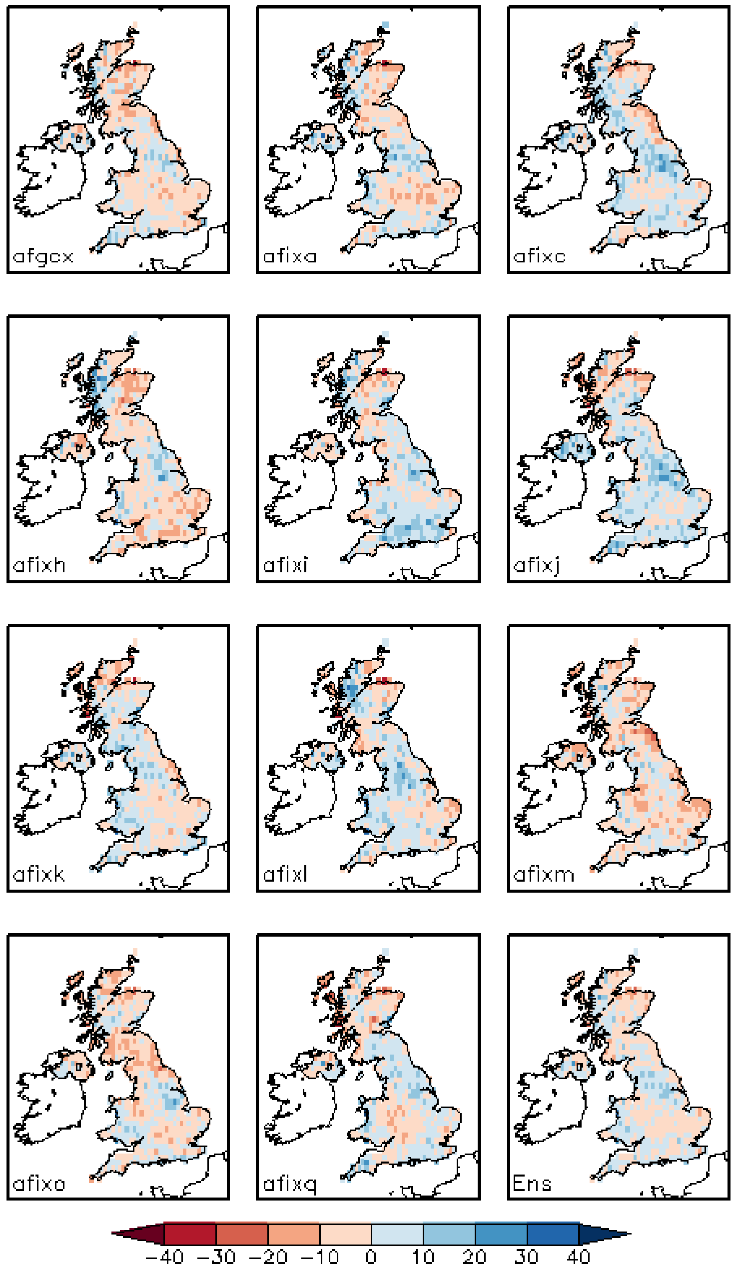

Figure A-16: As Figure A-15, but for moderate droughts.

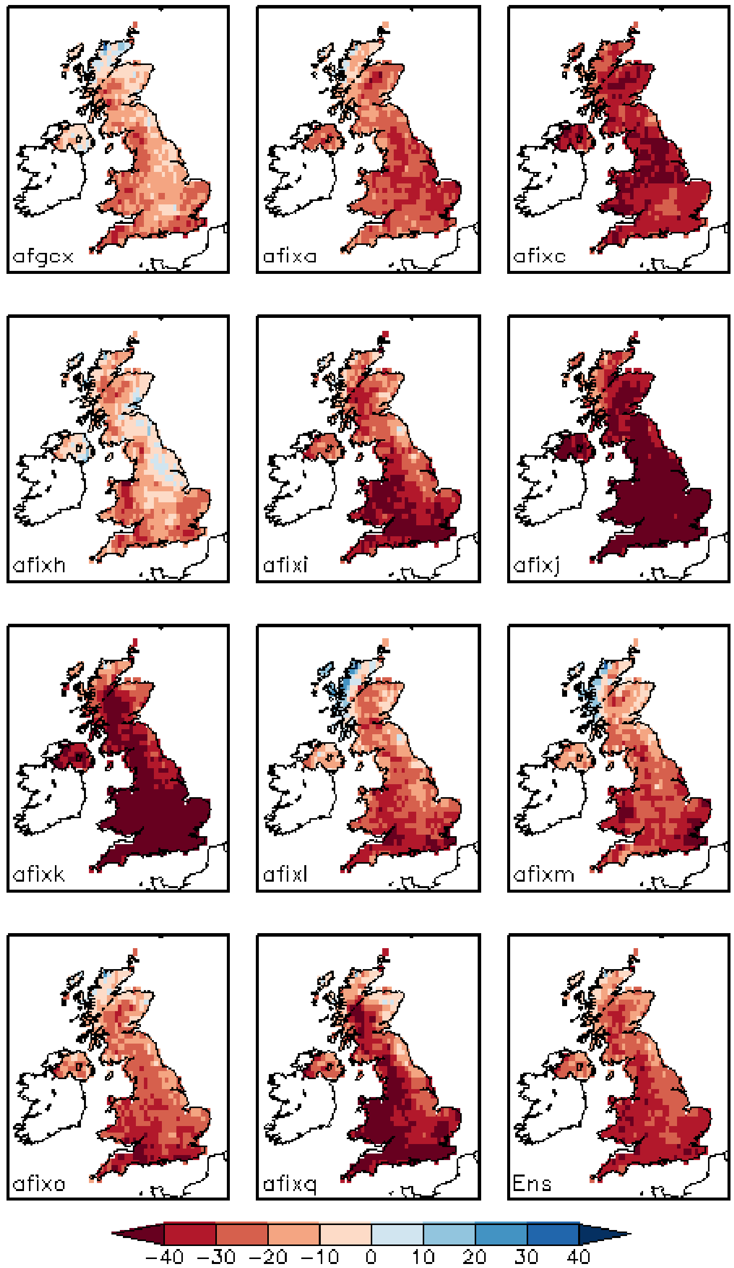

Figure A-17: Bias in frequency of drought months (*FDM*) during the dry season under moderate drought conditions for each of the 11-member ensemble (afgcx to afixq). Color bar shows the percentage change relative to the observed data. Ens refers to the ensemble mean bias.

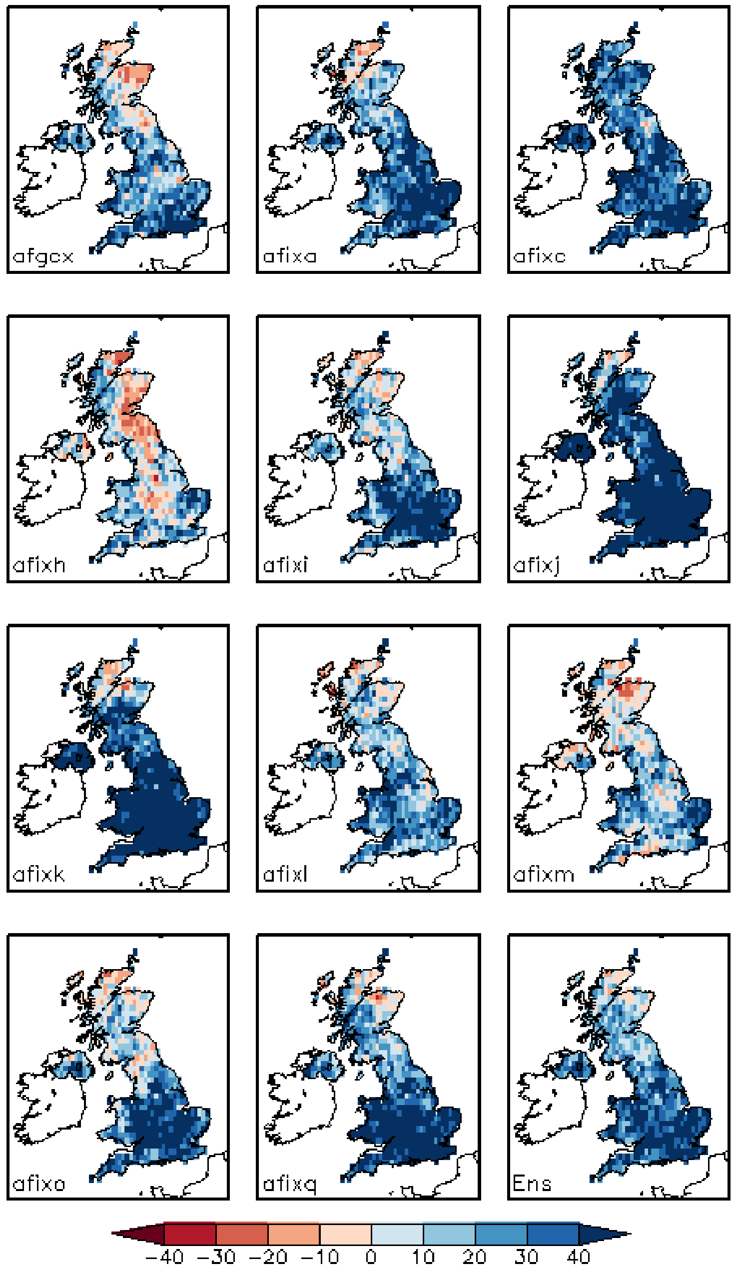

Figure A-18: Bias in frequency of drought months (*FDM*) during the wet season under extreme drought conditions for each of the 11-member ensemble (afgcx to afixq). Color bar shows the percentage change relative to the observed data. Ens refers to the ensemble mean bias.

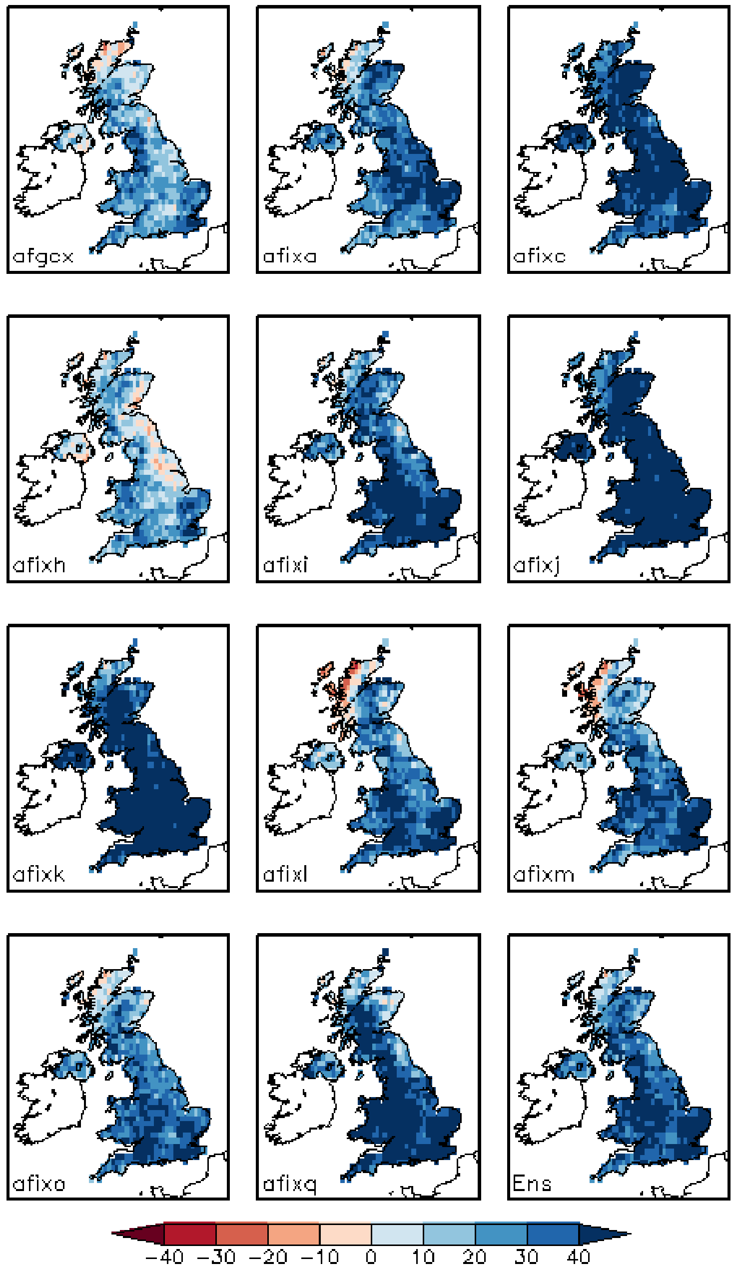

Figure A-19: As Figure A-18, but for moderate droughts.

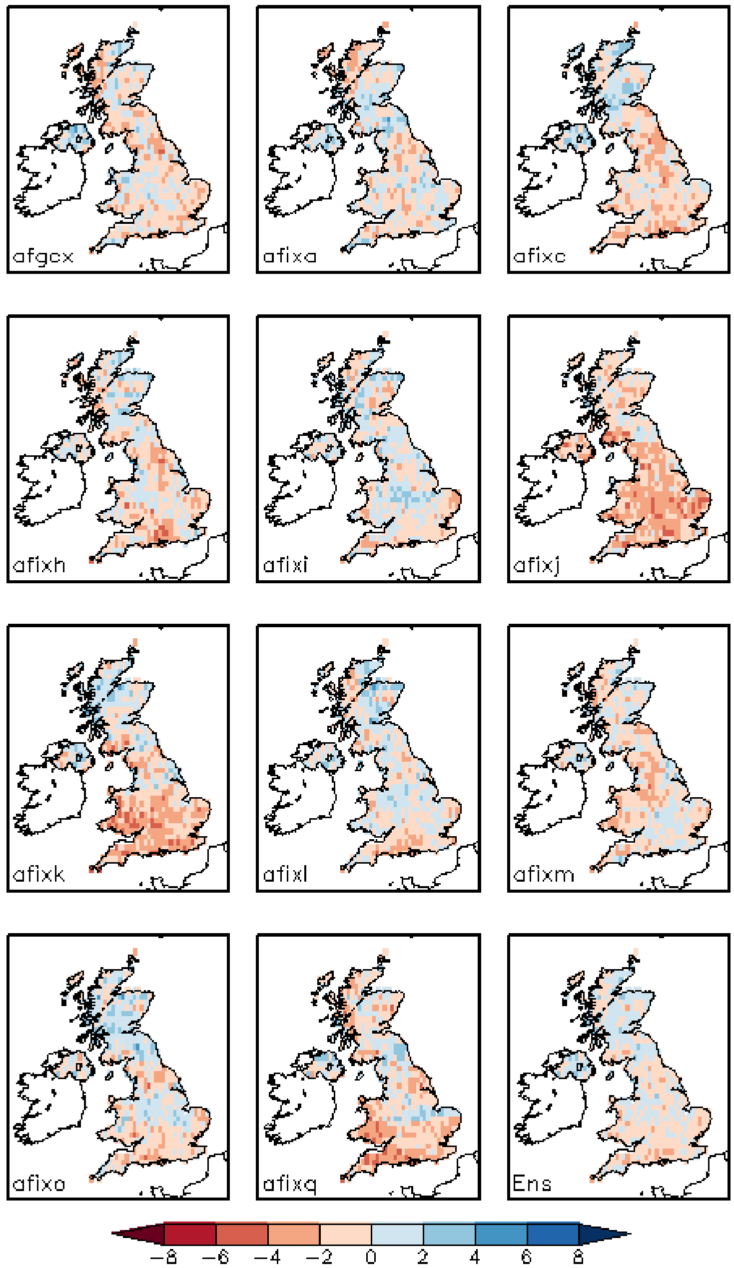

Figure A-20: Bias in frequency of drought events at a given duration (*FDD*) for extreme droughts with persistence of at least 6 months (FDD_6) for each of the 11-member ensemble (afgcx to afixq). Color bar shows the absolute change relative to the observed data. Ens refers to the ensemble mean bias.

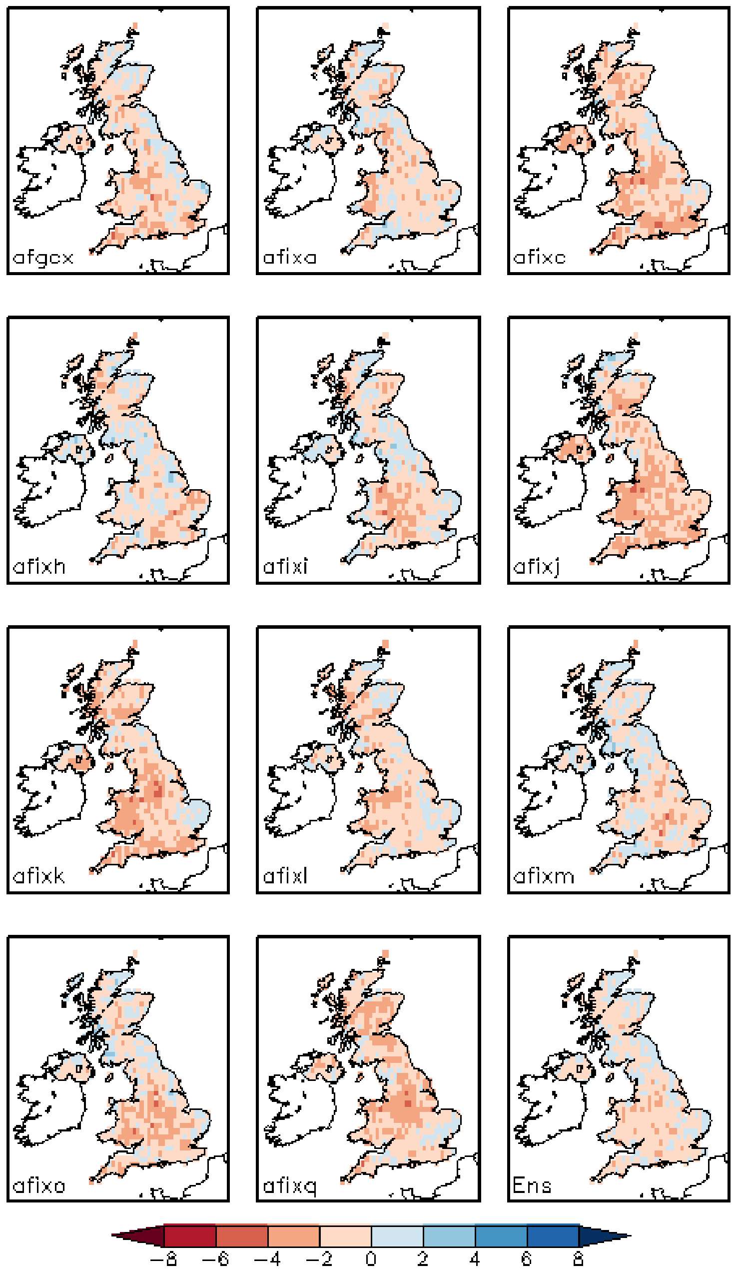

Figure A-21, Figure A-20, but for FDD_{10}.

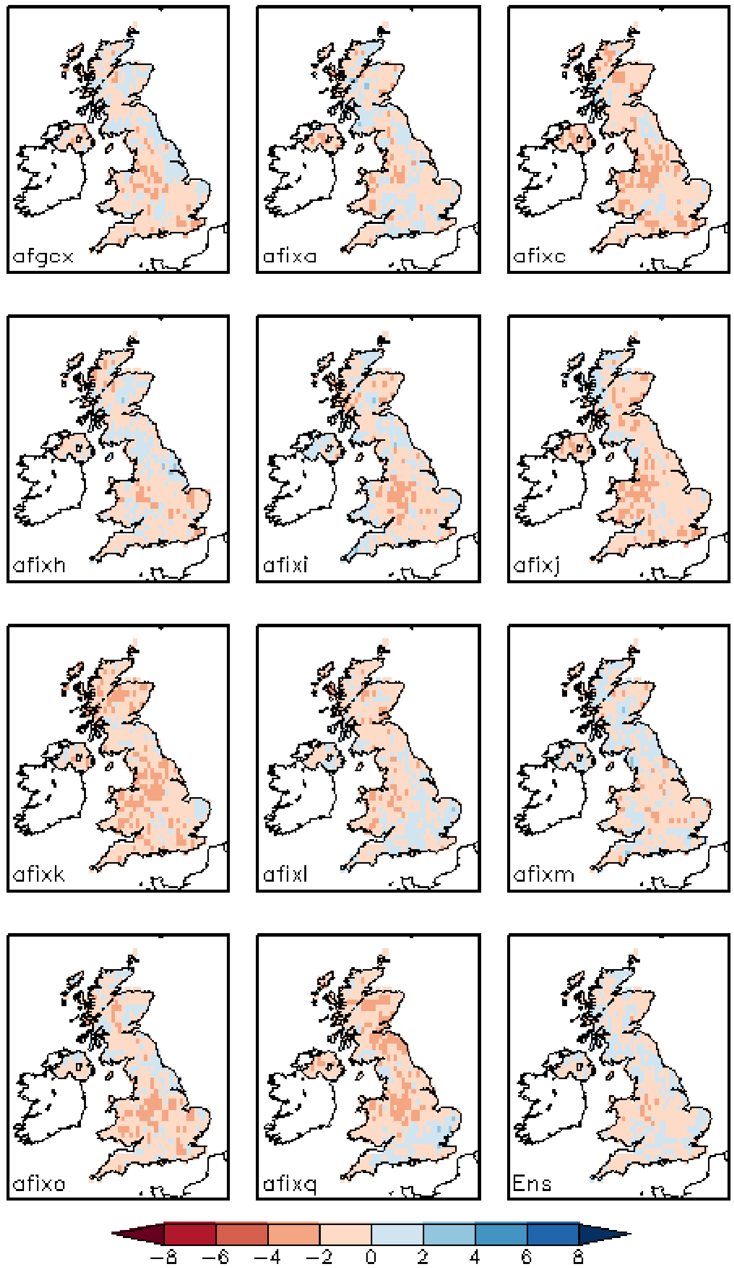

Figure A-22: As Figure A-20, but for FDD_{12}.

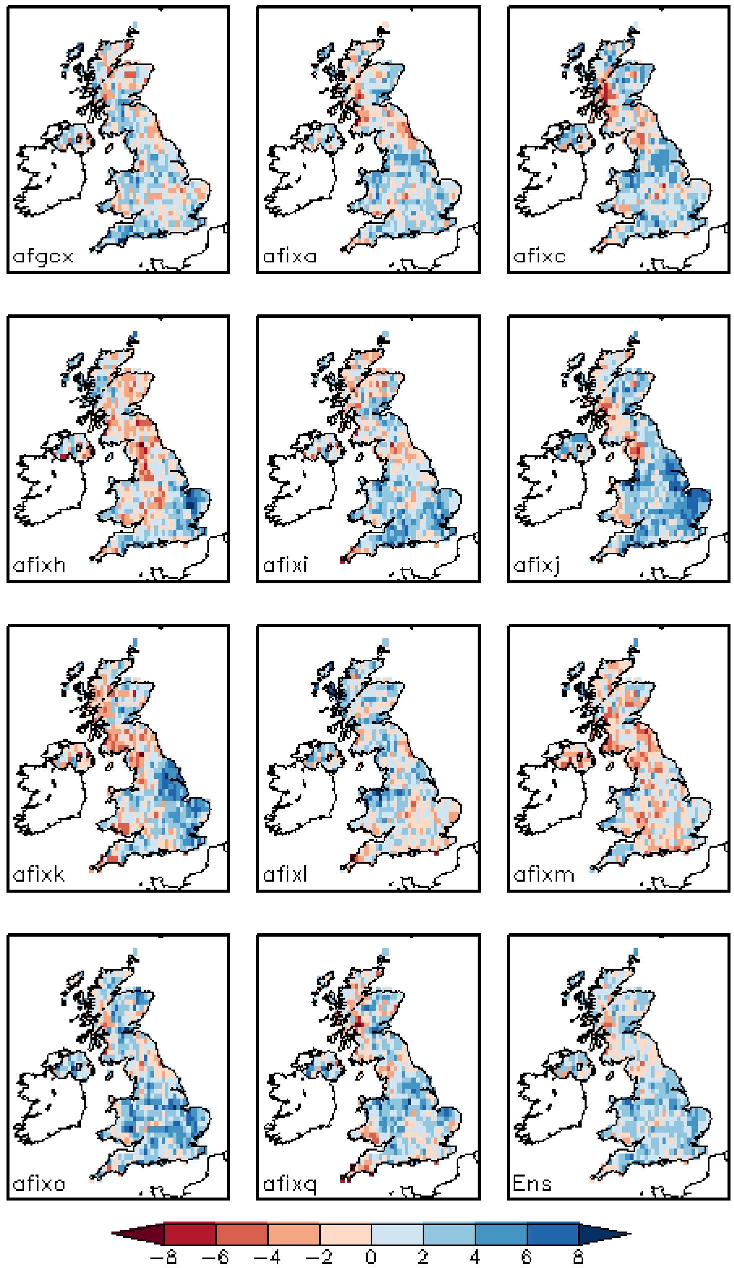

Figure A-23: Bias in frequency of drought events at a given duration (*FDD*) for moderate droughts with persistence of at least 6 months (FDD_6) for each of the 11-member ensemble (afgcx to afixq). Color bar shows the absolute change relative to the observed data. Ens refers to the ensemble mean bias.

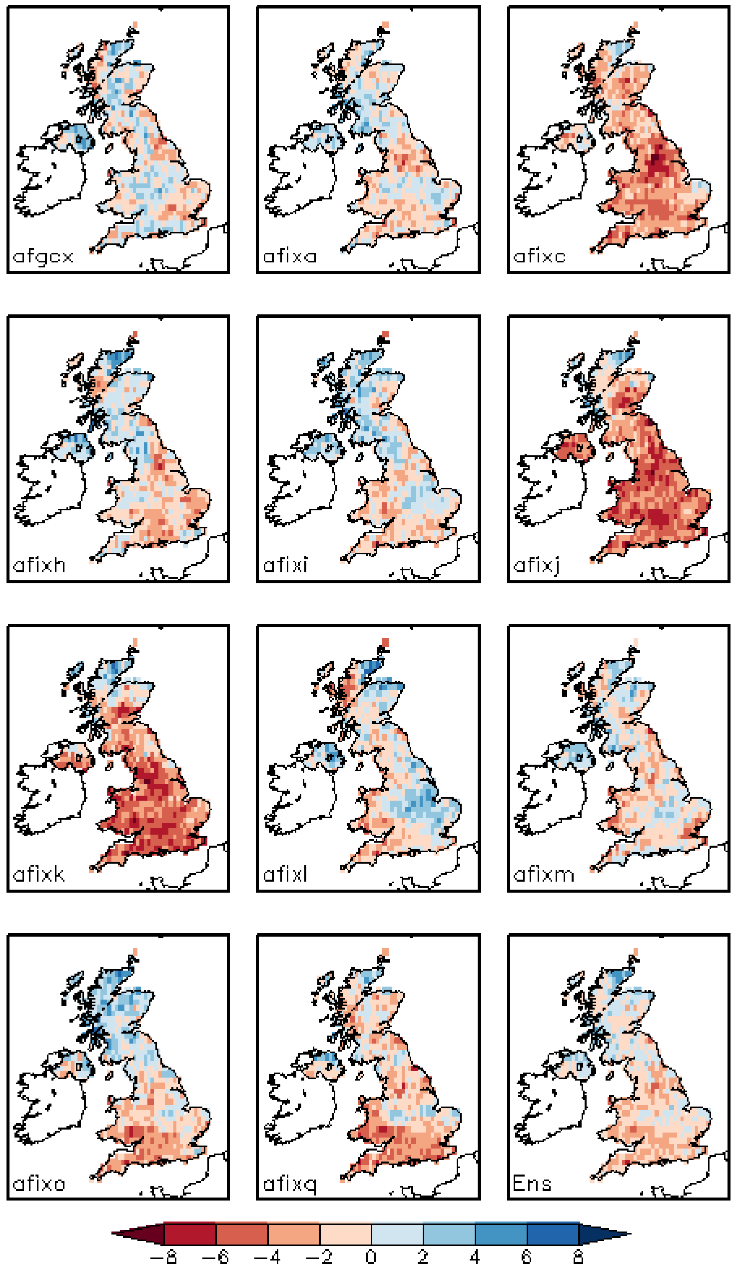

Figure A-24: As Figure A-23, but for FDD_{10}.

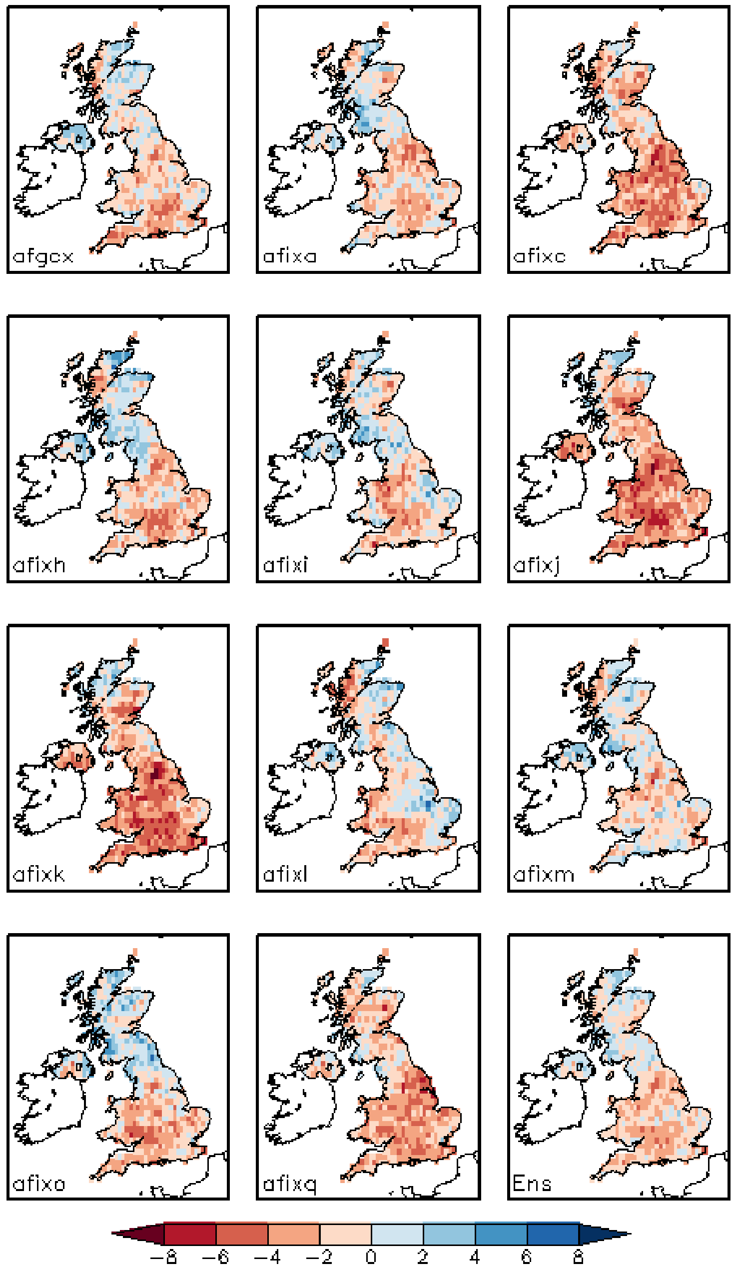

Figure A-25: As Figure A-23, but for FDD_{12}.