INTERNATIONAL JOURNAL OF CLIMATOLOGY
*Int. J. Climatol.* (2012)
Published online in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.3503

# An assessment of changes in seasonal and annual extreme rainfall in the UK between 1961 and 2009

Mari R. Jones,* Hayley J. Fowler, Christopher G. Kilsby and Stephen Blenkinsop
*School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne, UK*

**ABSTRACT:** There is a growing body of evidence supporting the Intergovernmental Panel on Climate Change's contestation that changes to hydrological extremes as a result of anthropogenic climate change are likely. There is also a growing level of concern among water resource managers about the nature of these changes and how we might adapt our behaviour to accommodate them. In particular, extreme multi-day rainfall events have been a significant contributing factor to the severe flood events of recent years.

Here we provide an updated study of extreme rainfall in the UK, focussing on changes to seasonal and annual maxima over the period 1961-2009. We employ regional frequency analysis to examine changes in the magnitude of estimated return periods obtained from generalized extreme value distribution curves. Return period estimates are analysed using both the full record and using 10 year intervals to determine the relative importance of natural variability and long-term changes in extreme rainfall distribution.

The magnitude of changes in estimated return periods are spatially varied, and dominated in northern and western parts of the UK by a periodic forcing such as the North Atlantic Oscillation (NAO), superimposed on normal seasonal fluctuations. In contrast, seasonality has the greatest influence on event magnitude in the south and east. We confirm that previously reported increases in spring and autumn extreme rainfall events have continued. Similarly, longer duration winter events have continued to increase in intensity, with a decrease in return period estimate from a 25-year to around a 5-year event over the full 50 years of record in parts of Scotland and Southwest England. In contrast, short-duration summer rainfall events have continued to decline in intensity, whereas longer duration events appear to be increasing in intensity. These results may have significant implications for flood defence design and planning, as well as to agricultural practices which may be sensitive to extreme rainfall. Copyright © 2012 Royal Meteorological Society

KEY WORDS regional frequency analysis; UK; rainfall; extremes; seasonality; GEV; climate change

*Received 4 August 2011; Revised 26 March 2012; Accepted 1 April 2012*

## 1. Introduction

Seldom does a day go by without reports of extreme events or climate records being broken in some part of the world. It is understandable, as the devastating consequences from extreme weather events enhance our awareness of their incidence far more than the occurrence of mean wet day rainfall. While the probability of a new record breaker increases with the length of the record (Benestad, 2003) and the difficulty of detecting changes in rainfall behaviour, particularly extremes, are acknowledged (Milly *et al.*, 2008; Fowler and Wilby, 2010) it is also highly likely that rainfall patterns are changing (Trenberth *et al.*, 2007). These changes and how to adapt to them are becoming increasingly important to policy makers, insurers, water resource managers and the general public alike.

There are two problems: one of assessing the probability of an extreme event occurring and the other of determining the likely future behaviour of these extreme events and their resultant impact on society. Emil Gumbel, noted that 'Il est impossible que l'improbable n'arrive jamais' [it is impossible that an unlikely event will never happen]; engineering design has long made use of Gumbel's theories on the extreme value distribution and subsequent developments to quantify the realistic probability of an event. This leads to the second problem of identifying the symptoms of the changing frequency of extreme events and whether future behaviour will continue in the same manner, for which there is an increasing body of literature and available software (World Meteorological Organization, 2009; Gilleland and Katz, 2011).

A responsibility lies with scientists to ensure that advances in climate change research, particularly in sensitive areas such as extremes of the hydrological cycle, are reflected properly in policy development. Some argue that we require better predictions of these extremes in order to adapt effectively to the changing climate (Dessai *et al.*, 2009) while others, the authors included, believe that a better understanding of exposure risk from the *environment* to the *development* in question is required in order to adapt effectively (McEvoy *et al.*, 2010).

---

* Correspondence to: M. R. Jones, School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne, UK.
E-mail: m.r.jones1@ncl.ac.uk

With the recent release of the Adaptation Sub-Committee (ASC) of the Committee on Climate Change's Report (Krebs *et al.*, 2010) assessing the UK's state of preparedness for climate change, there has been a shift in focus from whether climate change is occurring to determining the likely consequences. In particular, the ASC identified that in order to avoid maladaptation (that is adaptive actions which have a negative impact elsewhere, or at a later point in time), there is a need to quantify the UK's vulnerability to climate change. Nelson (2011) highlights that both individual and governance risk and decision frameworks are hampered by the lack of clarity and limited predictive power for future changes in extreme events.

It has been demonstrated by other researchers (Fowler and Ekström, 2009; Portmann *et al.*, 2009) that the influence of climate change on the hydrological cycle, while uncertain in its exact manifestation, will be an enhancement of precipitation variability particularly affecting the extremes. Karl and Trenberth (2003) observed that although total annual rainfall may be approximately unchanged around the world, there has been a trend towards fewer but more intense rainfall events. This observation is borne out by many other studies of rainfall across the UK (Fowler and Kilsby, 2003a, 2003b; Biggs and Atkinson, 2011), and worldwide (Alexander *et al.*, 2006; Pryor *et al.*, 2009; Liu *et al.*, 2011).

Different approaches have been used to assess extreme rainfall in the UK, employing various metrics such as the 95th percentile or the total rainfall on the 10 wettest days per year. Here we apply the generalized extreme value (GEV) distribution to estimate the likely magnitude of events from different predicted return periods, with practical application in engineering design, policy making or water resource management (Villarini *et al.*, 2011). Changes which have occurred and their approximate magnitude and direction can be determined by comparing the estimates from different periods of the observational record.

GEV models can also be used to characterize seasonal or location specific changes in frequency or magnitude. For example, Maraun *et al.* (2009) represented UK seasonality through a multivariate GEV model with a simple sinusoidal component fitted to monthly rainfall maxima. In contrast, Fowler and Kilsby examined the implications of changes to extreme rainfall from both seasonal (2003a, henceforth FK2003a) and annual (2003b, henceforth FK2003b) event magnitudes using a univariate GEV model, with an update to the analysis of annual maxima presented by Jones *et al.* (2010). In common with other studies, FK2003a found a downward trend in estimated summer extreme rainfall magnitudes, particularly for 1-d events in Southeast England, and the median seasonal maximum event (SMED). An increasing trend in estimated winter extreme rainfall magnitudes was apparent with the greatest increases in Scotland. However, in contrast with Osborn and Hulme (2002), limited change in England and Wales.

This paper is motivated by a need to revisit the original work by Fowler and Kilsby to update their analyses from 1961 to 2000 to the present (2009), and to compare the results with other recent publications on UK extreme rainfall. Changes in the seasonal occurrence of extreme rainfall events have had significant impacts on the food and drink industry with heavy rain damaging recently planted crops (Rosenzweig *et al.*, 2002), in addition to an increased flood potential resulting from severe rainfall on either arid or saturated ground. We aim to quantify seasonal and regional differences in the changes in maximum rainfall around the UK to inform those involved with adaptive action planning, from the individual farmer to the policy maker.

This paper first describes the dataset and methodology employed in Section 2, before presenting trends in the updated annual and seasonal maxima in Section 3, together with an assessment of trends in rolling decadal medians. We examine changes in the regional return period estimates in Section 4 and discuss their implications for future UK water resource management in Section 5. Section 6 summarizes our conclusions.

## 2. Methods and data

### 2.1. Dataset

Changes in seasonality were examined using observations from 223 daily rainfall records, updating the 204 originally used by FK2003a and FK2003b from 2000 to 2009. The gauged data were pooled into nine UK rainfall regions, each region containing $\geq 15$ gauges for 2000–2009 or $\geq 20$ for the period 1961–2000. These regions are depicted in Figure 1, with the locations of all 223 gauges and an indication of the analysis period covered by each gauge. Daily rainfall data for the period 2000–2009 were supplied by the British Atmospheric Data Centre (BADC, http://www.badc.rl.ac.uk) for all gauges within the UK, with additional data obtained from Durham University, the Rothamsted Research Archive and the Met Office. Where it was not possible to update an observation series, alternative gauges were sought from previously compiled work (Osborn and Hulme, 2002) to achieve the target minimum in each region. Jones *et al.* (2010) describe the process of selecting and updating the records and the identification of the minimum pool size.

### 2.2. Methodology

This study made use of nine homogenous UK rainfall regions (Wigley *et al.*, 1984) digitized by Alexander and Jones (2000). It could be argued that rainfall regions derived from mean daily observations are inappropriate for a study of annual maxima (Dales and Reed, 1989). The discordancy measure (Hosking and Wallis, 1997), which assesses the similarity of different station annual maxima distributions within a pool, was employed to verify the homogeneity of the regions; this facilitates comparison with previous research. Further details of

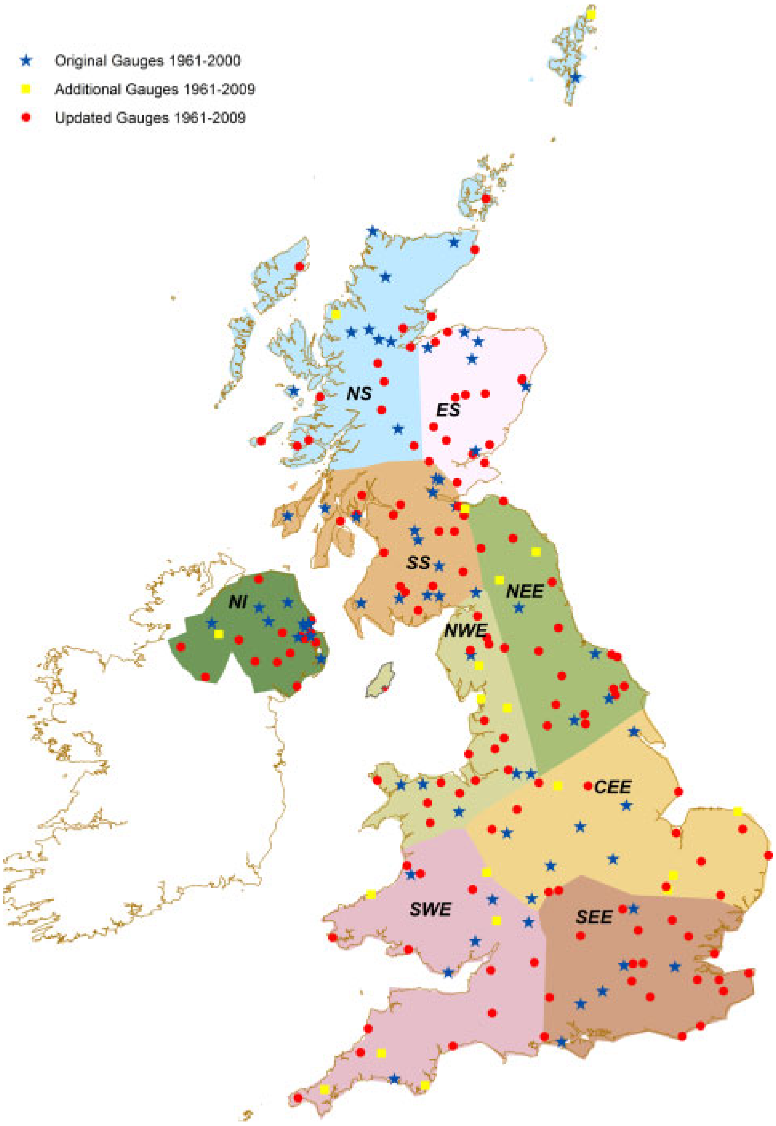

Figure 1. Location of the 223 UK daily rainfall records with complete or almost complete data for the 1961–2009 period and the nine UK rainfall regions. The regions are North Scotland (NS), East Scotland (ES), South Scotland (SS), Northern Ireland (NI), Northwest England (NWE), Northeast England (NEE), Central and Eastern England (CEE), Southeast England (SEE) and Southwest England (SWE). Red spots indicate the 133 gauges used by FK2003a and FK2003b which were updated to 2009; blue stars indicate the 71 gauges which terminated in 2000; yellow squares indicate 19 supplementary gauges. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

the homogeneity calculation are provided by Jones *et al.* (2010) and FK2003b.

We adopted a regional frequency analysis (RFA) methodology (FK2003b), standardizing time series of individual gauge maxima by the gauge median (1961–1990) to remove orographic or exposure effects prior to pooling. Regional seasonal and annual medians (SMED and RMED, respectively) were calculated from the weighted mean of all gauges in the region, where individual stations were weighted according to record length to reflect the reliability of the relevant set of observations (Hosking and Wallis, 1988) as:

$$w_i = \frac{n_i}{\sum_{i=1}^{N} n_i} \tag{1}$$

where $w_i$ is the effective record length at the $i$th site, $N$ the number of sites in the pooling group and $n$ represents the number of station years.

Changes in the magnitude of estimated return periods were examined using the GEV distribution. GEV distribution curves were fitted to the 1-, 2-, 5- and 10-day seasonal and annual standardized pooled maxima using maximum likelihood estimates (MLEs) of the parameters and return period estimates obtained by multiplying by the regional SMED or RMED. In contrast, FK2003a and FK2003b calculated the L-moments of individual gauges to fit the regionally pooled GEV distributions; in the presence of an external influence such as changing climate or covariate data, MLE has been shown to be more appropriate (Zhang *et al.*, 2005). A further advantage of the MLE methodology is that standard error estimates are inherently calculated, whereas L-moment ratios require further manipulation to determine the confidence limits. Parameter uncertainties were estimated with a bootstrap by replacement method (Efron, 1979), rather than relying on those obtained directly through the MLE calculations, to account for the reduced independence between the maxima following pooling. For further information on fitting the GEV distribution in general, please refer to Coles (2001), and for the specific methodology to Jones *et al.* (2010) or FK2003b.

Three methods were adopted to examine potential changes in return level estimates and median values (annual and seasonal):

- Fixed decades (1961–1970, ..., 1991–2000);
- Rolling decades (1961–1970, 1962–1971, ..., 2000–2009);
- Datasets covering 1961–2000 and 1961–2009.

Method 2 enhances method 1 by verifying that apparent changes in the fixed decades are not merely artefacts of the selected time period. Method 3 allows a more comprehensive assessment of the influence of recent maxima between 2000 and 2009 on the return period estimates.

Events considered for this study are the 1-, 2-, 5- and 10-day maximum daily total per annum or season; return period estimates are calculated for an idealized set of 10-, 25-, 50- and 100-year events for each of the fixed and rolling ten year groups, acknowledging that estimates of the 100-year event are not necessarily reliable. Following the Flood Estimation Handbook (FEH) rule of thumb (Faulkner, 1999), a dataset at least five times the length of the target return period (T) should be used in estimation. As $T = 100$ exceeds the maximum valid estimate from a minimum pool of 15 gauges for North Scotland in the period 2000–2009 we concentrate mainly on changes in higher frequency return periods in this paper (i.e. T $\leq 50$, dependent on the pool size). Seasonal maxima and associated return period estimates are analysed using fixed block seasons: Spring (MAM), summer (JJA), autumn (SON) and winter (DJF). For clarity, we refer to events with the numeric form (e.g. 5-day, 25-year) and analysis periods with the alphabetic form (e.g. rolling ten year group).

## 3. Updated annual and seasonal maxima

### 3.1. Standardized regional annual maxima

Before fitting GEV distributions to the regionally pooled maxima, we first examined the standardized pooled series for differences from those produced by FK2003b. The purpose was twofold: to determine the influence of incorporating different data sets on the regionally pooled results, and to identify any recent changes. The annual rainfall maxima for all duration events were standardized for each site and pooled regionally, regional standardized annual maxima (AMAX) series for 1961–2009 are shown in Figure 2 for the different duration events. Plotting positions, $y$, for the fitted distribution were determined from the Gringorten formulae (1963):

$$F_i = \frac{(i + 0.44)}{(N + 0.12)} \tag{2}$$

$$y = -ln(-ln(F_i)) \tag{3}$$

where $F_i$ is the non-exceedance probability, $i$ the rank in ascending order and $N$, the number of pooled maxima.

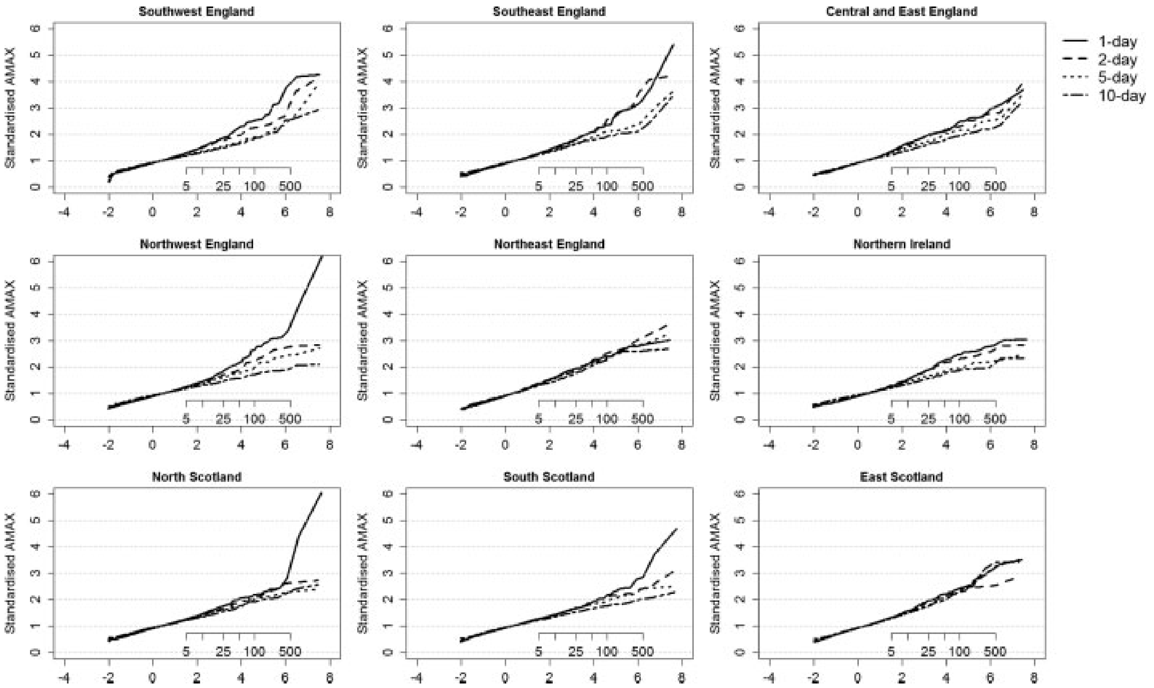

Figure 2. Standardized regional annual maximum (AMAX) rainfall distributions 1961–2009 for the nine pooling regions (update of FK2003b Figure 3).

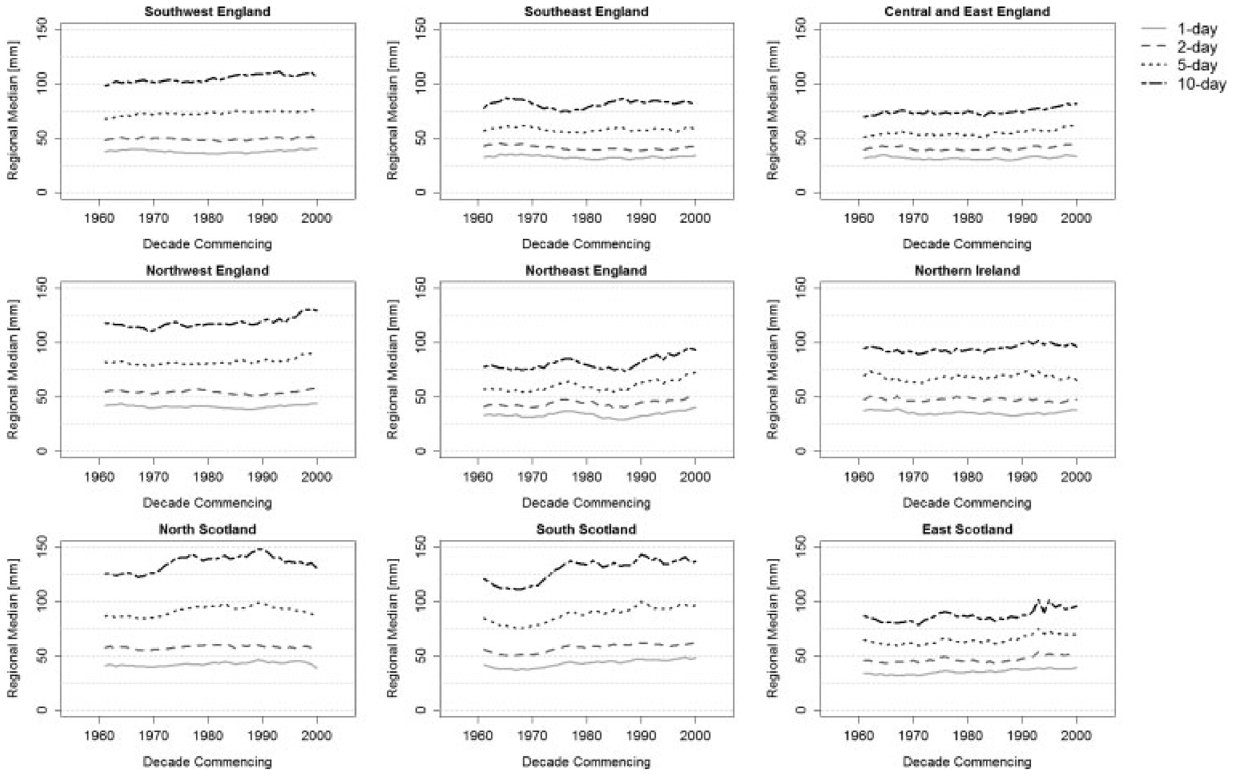

Figure 3. Decadal mean regional median annual maxima (RMED).

Comparison of Figure 2 with FK2003b Figure 3 shows that most regions have higher extreme values of standardized annual maxima. Some of the increases in the extremes relate to annual maxima recorded during the period 1961–2000 at the 19 supplementary gauges so invalidating any direct comparison. However, several regions (CEE, NWE, NEE, SS and NS) have higher extremes resulting from recent events such as July 2007, affecting CEE and SWE with 147 mm recorded over a 48-h period at Pershore Agricultural College, September 2008 in NEE with 152 mm in 48-h at Morpeth and the UK record 24-h total of 316.4 mm recorded in Seathwaite, NWE in November 2009. An exception to this pattern is East Scotland, due to the re-allocation of Edinburgh Botanic Gardens from East Scotland to the South Scotland region, following an assessment of the digital regional boundaries and homogeneity testing referred to in Section 2. As will be demonstrated in later sections, the station re-allocation has not had an undue influence on the results for either region when compared with the influence of more recent extreme events.

The extra data for 2000–2009 have made most growth curves steeper, with the exception of Northeast England (NEE) and Northern Ireland (NI) where little change is observed, indicating more variance in magnitude between different return period events. That is, where the 1-day 10-year return period estimate (10% annual probability) might be 50 mm and the 100-year return period estimate (1%) 75 mm, these may now be 55 mm and 90 mm, respectively. More detailed comparison of the revised estimates is provided in Section 4.

## 3.2. Trends in RMED and SMED

We also examined changes in the mean regional RMED and SMED for rolling ten year periods, which exhibit a high degree of spatial variability (Figures 3 and 4) with no fixed pattern for any region or season. Rolling decade statistics were calculated from the first year of the ten year period analysed, the $x$-axis on Figures 3 and 4 (and subsequent similar figures) reflects the start year of each ten year period. Most regions, other than NI and SEE, exhibit a significant upward trend in RMED for all duration events, particularly in the north and west, e.g. approximately 36 mm from 1961 to 2009 in South Scotland (SS) 10-day maxima. Changes in SMED are more apparent in longer duration events (5- and 10-day) with significant increases across all regions in winter, again with the largest increases in SS. Spring and autumn medians also appear to be increasing, although both the magnitude and the significance of the increase are weaker in the east; summer medians are significantly decreasing in southern area. Trend significance for each region was tested using a moving-block bootstrap (Efron and Tibshirani, 1993), of block length $L = 5$, to establish the confidence intervals over each decade while reflecting the relative decrease in data during the most recent decade (2000–2009).

Table I presents the magnitude per year of linear trends in each region, and estimated significance in parentheses, for the regional RMED and SMED series. Trends were assessed using the Mann-Kendall statistic, with a significance level of 5%, as rank based tests are more appropriate for non-normally distributed data (Yue

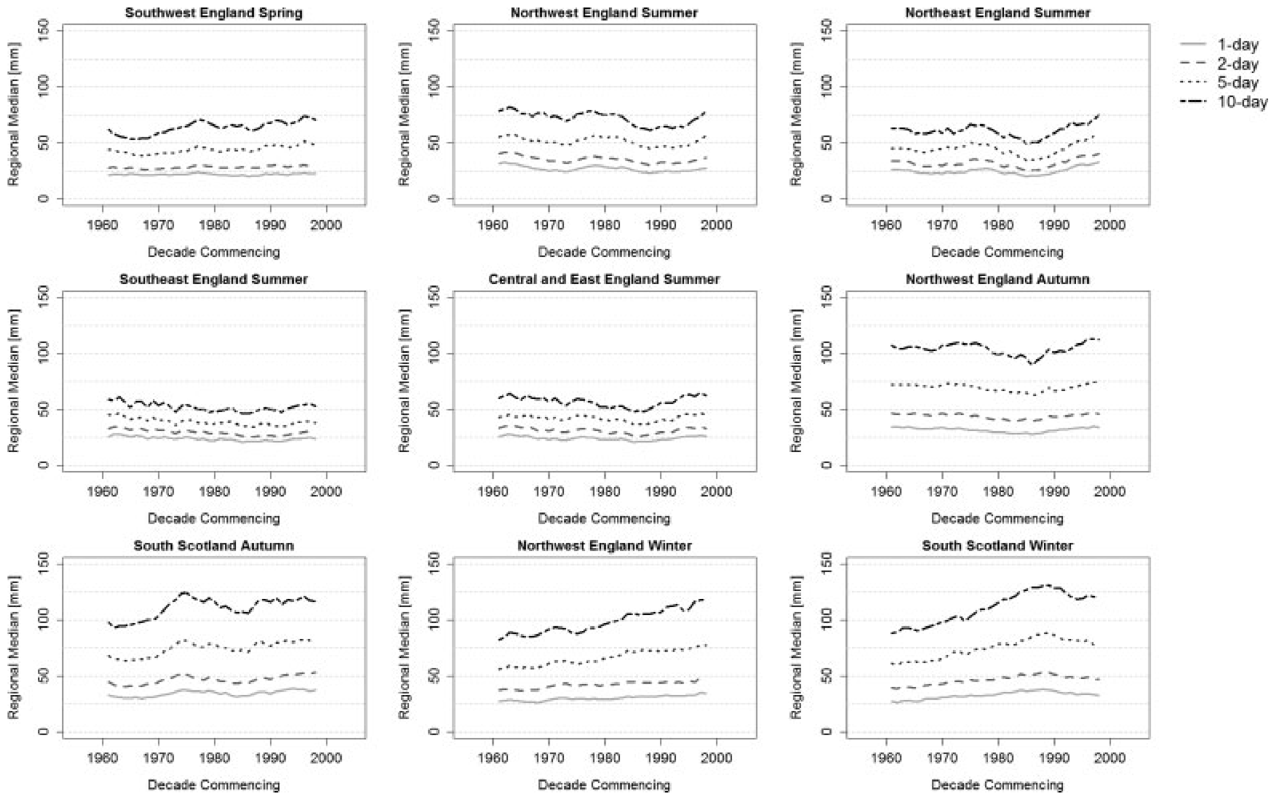

Figure 4. Trends in the regional median seasonal maxima (SMED) for SWE in spring; NWE, NEE, SEE and CEE in summer; and NWE and SS in autumn and winter.

and Pilon, 2004). Despite the autocorrelation introduced by the rolling decade approach, we found that a bootstrap technique did not alter the trend results or standard error estimates. Trends in shorter duration events equate to around 4 mm over the period of record, and could arise from random atmospheric fluctuations (Benestad, 2003). In contrast, significant increases in longer duration winter rainfall approximate 40–50 mm over the period of record and could have severe implications on flood generation.

In common with FK2003a and more recent research (Maraun *et al.*, 2008), a consistent increase in magnitude is evident in most regions for spring and autumn SMED, although the test results are only significant in northern regions. Contrasting results are apparent for the summer SMED, with some regions exhibiting decreases followed by a rise towards the end of the record (e.g. SEE, CEE) and others showing overall increases (e.g. NEE). Recent summer events which have been particularly intense over southwest and central England (e.g. Boscastle in 2004; Gloucester in 2007) have probably influenced the rise at the end of the record in these regions. Test results correspond to a significant decrease in short-duration events in the summer in NI, SEE, SWE and NWE, with less conclusive results for longer durations and other regions. Winter medians are increasing, by varying amounts, most notably in NWE, NS and SS for long duration (5 and 10 d) events.

Table II shows the mean RMED values for each pooling region in each of the fixed decades. The exact numbers differ from those published by FK2003b; however, the same behaviour is observed, with most regions experiencing an increase in RMED over the last two decades, particularly the north and west. The decade 1991–2000 was dominated by some exceptionally heavy long duration events, and this is reflected by the higher means in 5- and 10-day events for many regions. While the highest mean RMED for 10-day events generally occurred during 1991–2000, in most regions there has been an overall increase in magnitude since 1961–1970.

A recent work (Allan *et al.*, 2009) has correlated this inter-decadal variability with fluctuations in large-scale teleconnection patterns, such as the North Atlantic oscillation (NAO). The winter NAO index for the period from 1961 to 1990 was positive for several consecutive years interspersed with solitary negative winters, with few years experiencing particularly high or low index values. In contrast, the most recent two decades have experienced several exceptionally high and low NAO years. When the NAO is negative, westerly winds tend to be weaker leading to lower rainfall totals; the converse tends to occur in positive NAO years, particularly in western regions, with exceptional events in particularly high NAO years such as 1991 and 1999. While the impact of increasing global temperatures on the NAO signal is not fully understood, the most negative winter NAO indices on record for both 2008 and 2009, accompanied by record global mean temperatures, also appear to have led to exceptionally heavy events in both years.

Some of the changes in RMED are reflected in or explained by the SMED indices. As peak short-duration

Table I. Magnitude per year of linear trends calculated with a block bootstrap, of mean decadal RMED and SMED by region over the period 1961–2009 for 1-; 2-; 5- and 10-day events.

| Pooling region | RMED | Spring | Summer | Autumn | Winter |
|---|---|---|---|---|---|
| 1 d | | | | | |
| SWE | 0.01 (0.66) | 0.01 (0.13) | −0.07 (0) | 0.05 (0) | 0.08 (0) |
| SEE | −0.05 (0.02) | 0.01 (0.54) | −0.12 (0) | 0.04 (0.03) | 0.09 (0) |
| CEE | 0.01 (0.78) | 0.01 (0.45) | −0.05 (0.04) | 0.1 (0) | 0.07 (0) |
| NWE | 0 (0.78) | 0.02 (0.13) | −0.15 (0) | −0.06 (0.01) | 0.16 (0) |
| NEE | 0.08 (0.07) | −0.03 (0.29) | 0.07 (0.57) | 0.04 (0.13) | 0.16 (0) |
| NI | −0.05 (0.07) | 0.06 (0) | −0.11 (0) | −0.02 (0.55) | 0.07 (0) |
| NS | 0.1 (0) | 0.08 (0) | −0.02 (0.28) | 0 (0.35) | 0.16 (0) |
| SS | 0.28 (0) | 0.16 (0) | 0.03 (0.15) | 0.14 (0) | 0.23 (0) |
| ES | 0.18 (0) | 0.14 (0) | 0 (0.7) | 0.16 (0) | 0.12 (0) |
| 2 d | | | | | |
| SWE | 0.02 (0.38) | 0.06 (0) | −0.12 (0) | 0.1 (0) | 0.19 (0) |
| SEE | −0.11 (0) | 0 (0.86) | −0.17 (0) | 0.01 (0.45) | 0.19 (0) |
| CEE | 0.05 (0.03) | 0.02 (0.52) | −0.08 (0.02) | 0.11 (0) | 0.1 (0) |
| NWE | −0.01 (0.6) | 0.05 (0.01) | −0.19 (0) | −0.07 (0.01) | 0.23 (0) |
| NEE | 0.16 (0) | −0.04 (0.25) | 0.06 (0.7) | 0.09 (0.04) | 0.2 (0) |
| NI | −0.04 (0.15) | 0.09 (0) | −0.09 (0) | 0.02 (0.92) | 0.08 (0) |
| NS | 0.04 (0.1) | 0.08 (0) | −0.04 (0.16) | −0.04 (0.01) | 0.22 (0) |
| SS | 0.29 (0) | 0.19 (0) | 0.04 (0.06) | 0.21 (0) | 0.31 (0) |
| ES | 0.17 (0) | 0.21 (0) | −0.07 (0.12) | 0.22 (0) | 0.14 (0.04) |
| 5 d | | | | | |
| SWE | 0.14 (0) | 0.2 (0) | −0.14 (0) | 0.29 (0) | 0.27 (0) |
| SEE | −0.03 (0.41) | 0.03 (0.62) | −0.21 (0) | 0.02 (0.38) | 0.24 (0) |
| CEE | 0.16 (0) | 0.07 (0.05) | −0.04 (0.3) | 0.14 (0) | 0.13 (0) |
| NWE | 0.18 (0) | 0.15 (0) | −0.18 (0) | −0.08 (0.05) | 0.57 (0) |
| NEE | 0.3 (0) | −0.01 (0.81) | 0.08 (0.6) | 0.19 (0) | 0.27 (0) |
| NI | 0.05 (0.17) | 0.15 (0) | −0.11 (0) | 0.09 (0.2) | 0.13 (0) |
| NS | 0.21 (0) | 0.25 (0) | 0 (0.67) | −0.1 (0.05) | 0.58 (0) |
| SS | 0.56 (0) | 0.3 (0) | 0.06 (0.2) | 0.41 (0) | 0.69 (0) |
| ES | 0.26 (0) | 0.21 (0) | −0.01 (1) | 0.42 (0) | 0.22 (0) |
| 10 d | | | | | |
| SWE | 0.26 (0) | 0.38 (0) | −0.25 (0) | 0.34 (0) | 0.33 (0) |
| SEE | 0.04 (0.56) | 0.1 (0.05) | −0.2 (0) | 0.06 (0.6) | 0.23 (0) |
| CEE | 0.18 (0) | 0.15 (0.02) | −0.09 (0.04) | 0.25 (0) | 0.13 (0) |
| NWE | 0.3 (0) | 0.24 (0) | −0.36 (0) | −0.03 (0.67) | 0.89 (0) |
| NEE | 0.34 (0) | −0.01 (0.86) | 0.06 (0.65) | 0.3 (0) | 0.37 (0) |
| NI | 0.19 (0) | 0.17 (0.03) | −0.05 (0.19) | 0.17 (0.03) | 0.13 (0) |
| NS | 0.39 (0) | 0.37 (0) | −0.06 (0.2) | −0.2 (0.06) | 1.01 (0) |
| SS | 0.75 (0) | 0.34 (0) | 0.03 (0.51) | 0.56 (0) | 1.14 (0) |
| ES | 0.34 (0) | 0.31 (0) | 0.03 (0.36) | 0.54 (0) | 0.25 (0) |

The significance measure is included in parentheses; values $\leq 0.025$ are significant against a two-tailed test.

events in the south and east mostly occur during late summer and autumn, trends in summer/autumn SMED match RMED trends for these regions. By contrast, regions dominated by westerly weather, with the heaviest rainfall occurring over longer durations in the winter, have winter SMED increases comparable with those in RMED.

Figure 5 indicates the typical seasonality of annual maxima events for 1- and 10-day duration events over the period 1961–2009. This illustrates how the seasonality in eastern regions is dominated by events in the summer, with 1-day events occurring later in the summer than 10-day. All other regions tend to experience short-duration events in late autumn, with little difference in timing between the regions. 10-day events have a wider spread of occurrence, ranging from late autumn to mid-winter, again with similar seasonality for all western and northern regions.

The few increases in summer SMED, although statistically significant, contrast with climate model projections which suggest that the future climate is likely to bring hotter, drier summers (Murphy *et al.*, 2009; Hopkins *et al.*, 2010). However, the results presented above and in later sections are premised on seasonal maxima rather than seasonal mean rainfall and it is known that both global and regional climate models are currently unable to simulate summer rainfall extremes because of inadequate parameterization of the convective processes (Fowler and

Table II. Mean RMED per decade for the nine pooling regions for durations (a) 1-; (b) 2-; (c) 5- and (d) 10-day.

| Pooling Region | 1961–1970 | 1971–1980 | 1981–1990 | 1991–2000 | 2001–2009 |
|---|---|---|---|---|---|
| (a) 1-day | | | | | |
| SWE | 37.8 | 38.1 | 36.1 | 38.4 | **40.8** |
| SEE | 32.7 | 34.6 | 30.3 | 32.5 | 33.9 |
| CEE | 32.0 | 31.1 | 30.7 | 33.2 | **33.4** |
| NWE | 42.2 | 40.9 | 41.5 | 41.2 | **44.1** |
| NEE | 33.4 | 32.6 | 34.7 | 33.1 | **40.9** |
| NI | 37.8 | 34.3 | 36.0 | 34.9 | 38.1 |
| NS | 41.2 | 40.5 | 44.0 | **44.3** | 39.2 |
| SS | 42.0 | 38.7 | 44.4 | 46.7 | **48.3** |
| ES | 34.0 | 32.5 | 36.1 | 37.6 | **39.3** |
| (b) 2-day | | | | | |
| SWE | 48.5 | 49.9 | 48.4 | **50.3** | 50.1 |
| SEE | 43.2 | **42.4** | 39.7 | 39.6 | 42.1 |
| CEE | 39.5 | 38.6 | 39.7 | 41.8 | **43.9** |
| NWE | 54.8 | 54.6 | 54.8 | 53.4 | **57.2** |
| NEE | 41.5 | 41.0 | 46.1 | 45.4 | **52.5** |
| NI | 47.8 | 45.9 | 48.8 | **49.0** | 47.6 |
| NS | 57.9 | 56.3 | **60.4** | 57.7 | 57.9 |
| SS | 55.8 | 51.8 | 59.2 | 61.9 | **62.5** |
| ES | 46.1 | 44.3 | 46.9 | 47.8 | **52.3** |
| (c) 5-day | | | | | |
| SWE | 67.8 | 72.9 | 73.9 | **74**.4 | **74.4** |
| SEE | 56.8 | **59.6** | 56.9 | 57.2 | 58.3 |
| CEE | 50.7 | 53.2 | 53.2 | 56.9 | **61.3** |
| NWE | 82.0 | 80.5 | 81.1 | 85.5 | **90.3** |
| NEE | 57.4 | 57.4 | 59.1 | 64.2 | **72.8** |
| NI | 70.0 | 63.1 | 68.5 | **74.0** | 65.6 |
| NS | 86.7 | 86.3 | 95.9 | **96.8** | 87.2 |
| SS | 84.7 | 78.6 | 92.4 | **98.1** | 96.7 |
| ES | 64.9 | 59.8 | 64.7 | 68.8 | **70.2** |
| (d) 10-day | | | | | |
| SWE | 98.3 | 101.9 | 105.3 | **109.4** | 106.1 |
| SEE | 77.6 | 79.7 | 80.4 | **82.8** | 80.2 |
| CEE | 69.8 | 73.3 | 74.1 | 75.9 | **82.0** |
| NWE | 117.7 | 113.6 | 117.3 | 121.4 | **129.8** |
| NEE | 78.2 | 78.6 | 78.2 | 85.9 | **93.3** |
| NI | 94.6 | 89.2 | 94.1 | **101.3** | 96.7 |
| NS | 125.7 | 128.5 | 139.6 | **145.1** | 130.5 |
| SS | 120.8 | 114.9 | 137.5 | **141.1** | 136.8 |
| ES | 87.3 | 78.8 | 87.6 | 87.4 | **95.7** |

The highest value of decadal RMED is shown in bold for each case. (Update of FK2003b Table III)

Ekström, 2009). Enhanced global mean temperatures are likely to cause a reduction of mean summer rainfall; however, a recent work has demonstrated that changes in extreme rainfall are likely to be greater than those in the mean (Allen *et al.*, 2002; Allan and Soden, 2008). At higher latitudes, where the moisture-adiabatic lapse rate is less important (Pall *et al.*, 2007), changes will be governed by the Clausius–Clapeyron relationship that describes increases in atmospheric moisture capacity as a function of temperature increase (Trenberth *et al.*, 2003). This would lead to increases in summer SMED and return period magnitudes, despite a commensurate increase in drought frequency (Frich *et al.*, 2002). The significant increases in winter SMED, especially within Scotland and more upland areas, may have arisen from less precipitation falling as snow (Jones and Conway, 1997).

## 4. Updated return period estimates

### 4.1. Changes in annual maximum return period estimates

MLEs of the GEV parameters were calculated for each of the regionally pooled, standardized AMAX series. The fitted GEV curves for each region are very similar in shape and scale to those obtained by FK2003b, confirming that no individual station maxima have a dominating influence on the fitted distributions and that notable differences are likely to result from the addition of the 2000–2009 data. Figure 6 shows regional return period

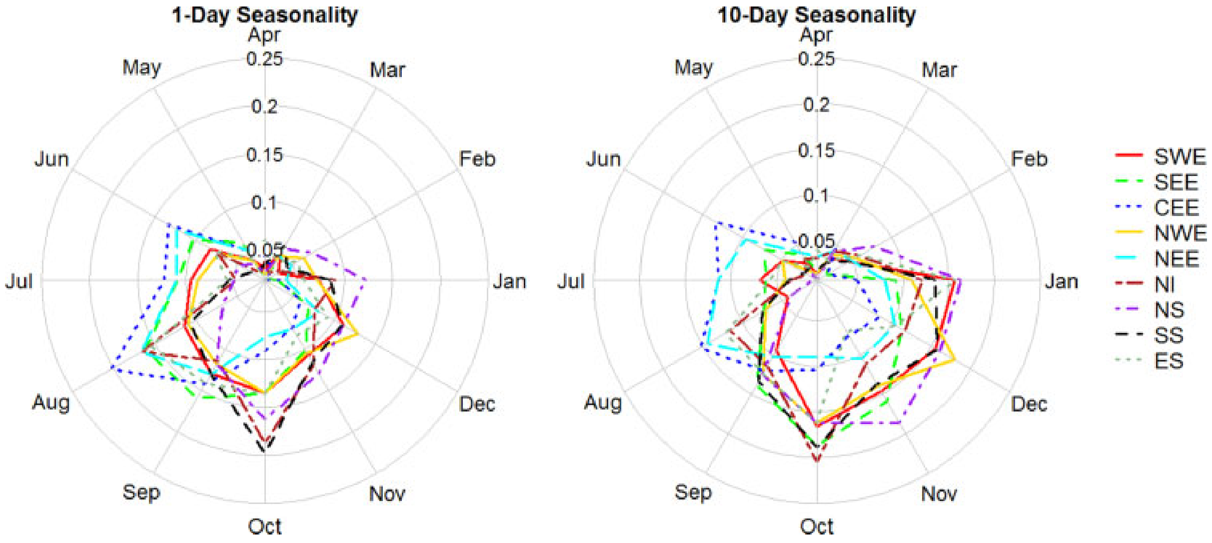

Figure 5. Regional timing of extreme rainfall events over the period 1961–2009 from (a) 1-d annual maxima and (b) 10-d annual maxima. Months are arranged radially with event frequency on the horizontal axis. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

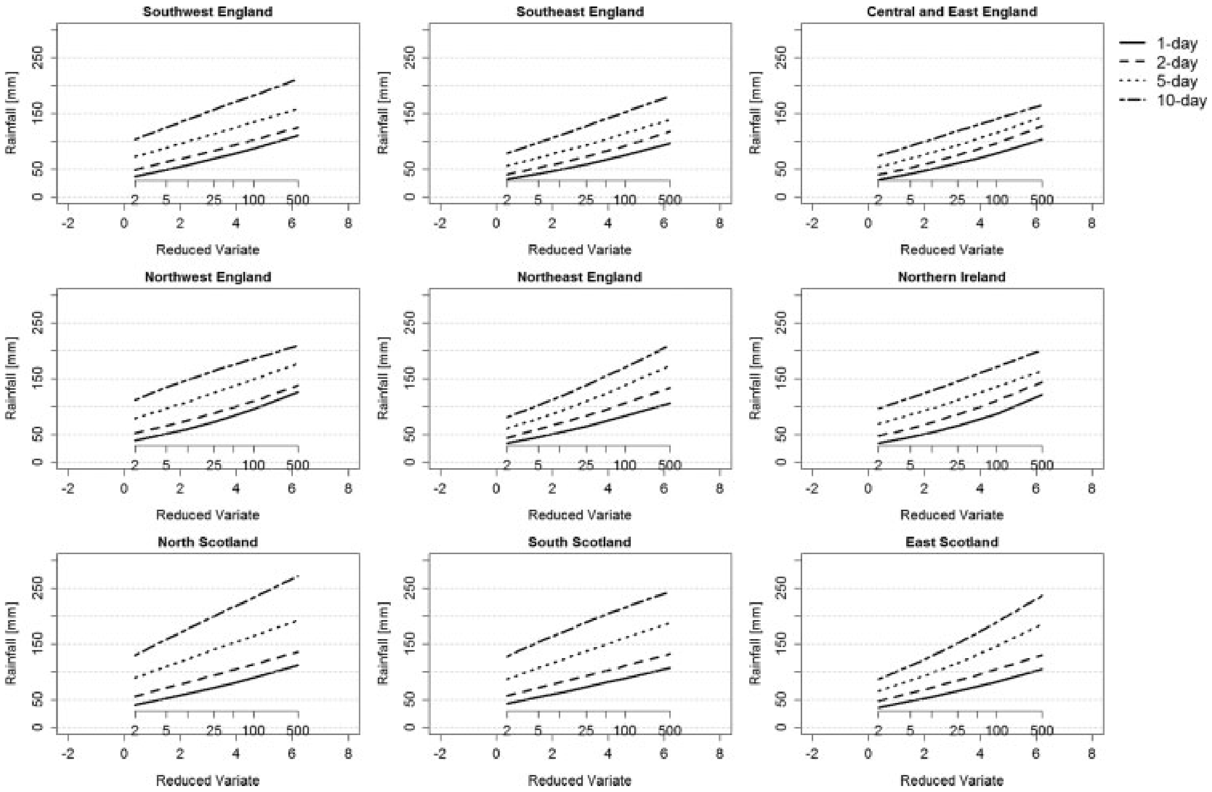

Figure 6. Fitted annual maximum GEV distributions 1961–2009 (using regional mean RMEDs). Update of FK2003b Figure 5.

estimates calculated from GEV growth curves multiplied by the regional RMEDs for the period 1961–2009 for each event duration.

We observe no coherent pattern in the differences from Figure 5 of FK2003b with respect to region or event duration; most differences in estimated magnitude are within the confidence limits and are either attributable to natural variability or minor changes in the pooling group. The SEE, NEE and ES regions exhibit the greatest differences in return period estimates and the growth curve shape. In SEE, all return period estimate curves have become flatter, with the greatest decreases in the upper tail of 1- and 2-day storms. Similarly, return period estimate curves for NEE are flatter but with larger peak values for all duration events. FK2003b reported that ES had experienced very wet conditions during the late 1980s and 1990s; Figure 6 indicates very little change from Figure 5 of FK2003b as recent events in East Scotland have not been as extreme and so had little influence on the return period estimates for this region.

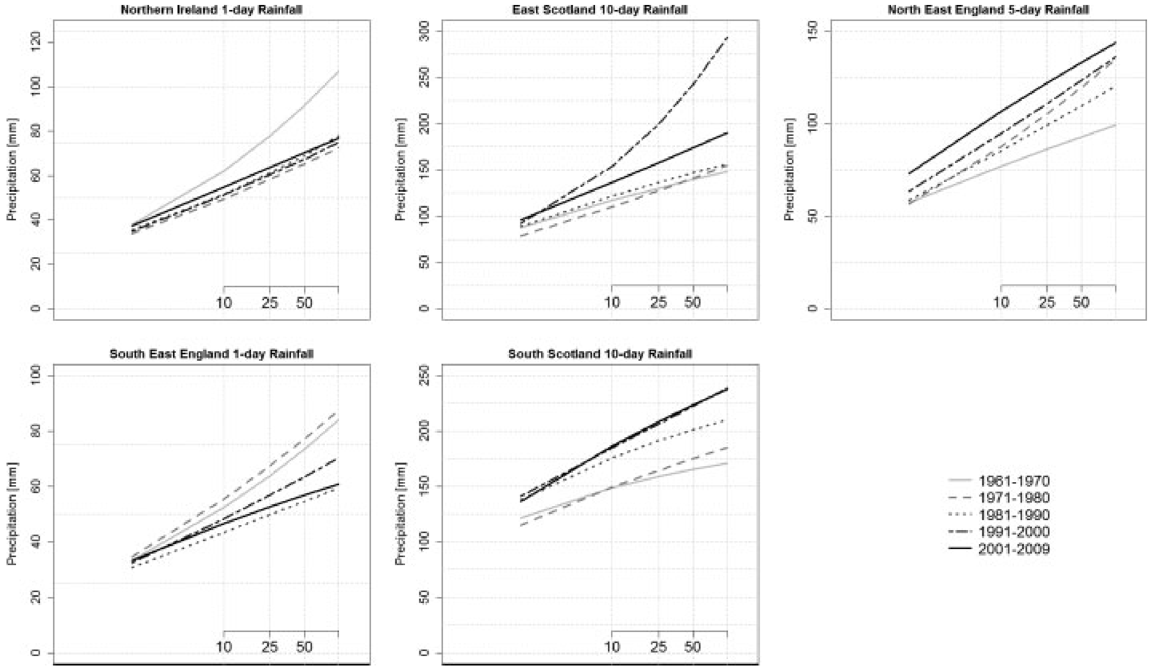

Figure 7. Fixed decade changes in return period estimates using mean regional RMED: (a) NI region, 1-day; (b) ES region, 10-day; (c) NEE region, 5-day; (d) SEE region, 1-day; (e) SS region 10-day.

### 4.2. Changes in decadal return period estimates

Differences between FK2003b estimates and the 1961–2009 estimates were explored in greater depth by using decadal changes to determine whether these result from periodic fluctuations or are part of a longer term change in behaviour. Two approaches were adopted: fixed decades (years xxx1 to xxx0); and rolling decades employing a sliding ten year window starting from 1961. The standardized AMAX for the $i$th year of decade $k$, at site $j$ ($X_{ijk}$) are calculated from the maximum rainfall for that year $P_{ijk}$ and the decadal median AMAX for site $j$ during decade $k$, $\mathrm{RMED}_{jk}$.

$$X_{ijk} = \frac{P_{ijk}}{\mathrm{RMED}_{jk}}$$

The results of both analyses, as illustrated in Figures 7 and 8, emphasize the variability between decades and the influence of exceptional years emphasizing the need to use as large as dataset as possible (Institute of Hydrology, 1999). Five regions show notable increases in the maxima and associated rolling decadal return period estimates over the full analysis period (1961–2009): NWE, NEE, SS and ES. Some regions (e.g. NI, ES) have sharp changes which clearly indicate extreme events entering and leaving the decadal calculations. The same features are also evident in the fixed decade analyses, where growth curves for the decade around the extreme event are considerably higher than those for other decades and could, if analysed in isolation, suggest a longer term change in behaviour. Other regions which display less contrast between the fixed decade estimates (e.g. SS) have much more noticeable increases when the rolling decade return period estimates are reviewed.

Fitted GEV curves for the SEE region were flatter in comparison to other regions for all durations, most notably for 1-day events (not shown); for full details of the results please refer to Jones *et al.* (2010). While the changes from decade to decade are small, the overall change in the 10-year event estimate since 1961 shows a significant decrease of approximately 15 mm. The flatter growth curve is a result of lower skew ($\kappa$) in the data, i.e. the variance in event magnitudes is decreasing, although the mean value may be heavier for all maxima. This is also reflected in the rolling decadal analysis (Figure 8(d)) by a reducing interval between the magnitudes of return period estimates in each ten year period and an apparent downward trend in the magnitude of shorter duration events over 1961–2009. The gradual increase in estimated event magnitude noted by FK2003b for 5- and 10-day rainfall in SS has continued into the most recent decade with a significant increase in magnitude. The magnitude of the estimated 100-year event (1% annual probability) in 1961–1970 has increased in frequency over the analysis period to approximately 10-years. Changes in return period estimates for ES found by FK2003b are replicated here in the rolling decadal analysis, with a peak over the 1990s in 5- and 10-day events (related to the events of September 1995) but then declining over the last decade. Despite the recent decline, there is a significant upward trend both in the estimated range and magnitude of events, with return interval estimates increasing from 25-year (4% annual probability) to 10-year frequency.

Figure 7 demonstrates that NEE fitted GEV distributions for fixed decades are progressively steeper since 1961–1970, although direct comparison between 1961–2000 and 1961–2009 indicates flatter curves for

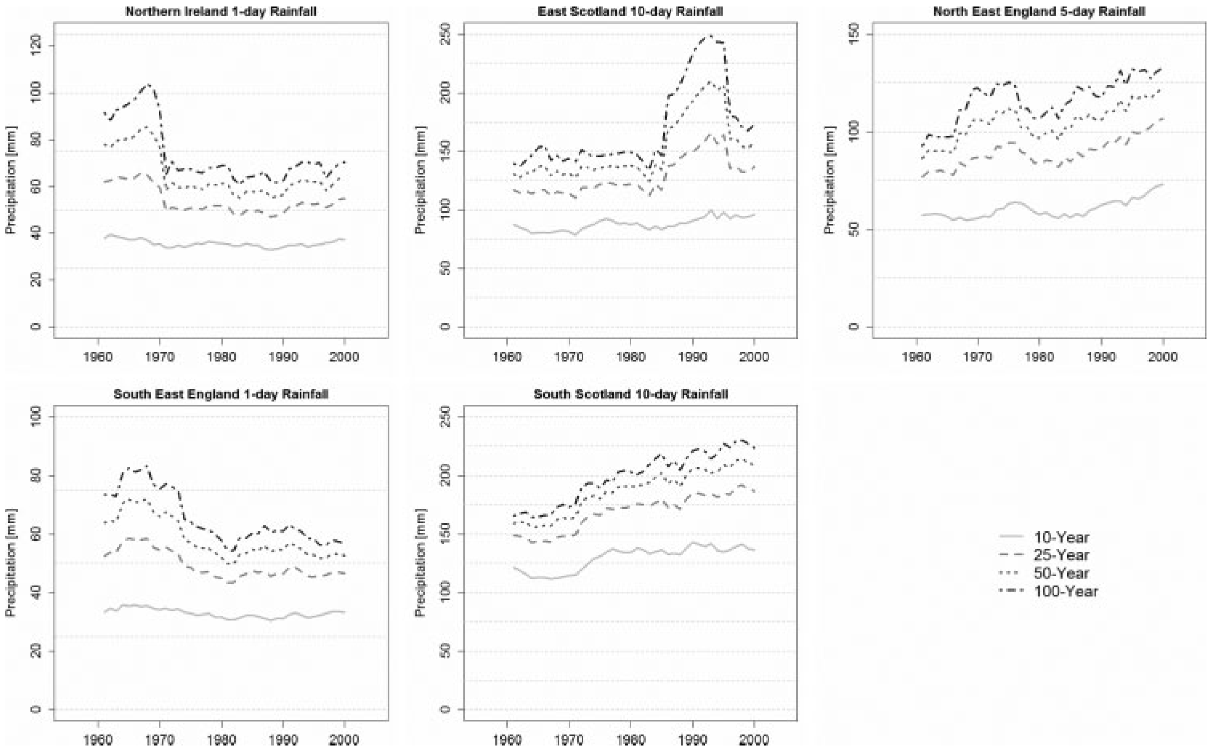

Figure 8. Rolling decadal return period estimates fitted for 1961–2009: (a) NI region, 1-day; (b) ES region, 10-day; (c) NEE region, 5-day; (d) SEE region, 1-day; (e) SS region 10-day.

the longer period. Inspecting the rolling decade results shows that there has been an increase in the range of return period estimates over the whole record in NEE in addition to a significant upward trend with increases in estimated event magnitude over the analysis period ranging from 15 mm (1-day) to 55 mm (10-day).

The results for Northern Ireland are highly variable and reveal no conclusive changes in return period estimates. In this region, the 1- and 2-day events exhibit similar behaviour in the rolling decadal distribution estimates, with a step change in estimated magnitude at the end of the first decade (1961–1970) of around 20–30 mm, before continuing to vary about a lower median. This pattern is not repeated in the 5- or 10-day events, which peak later in the record; the longer duration events are more suggestive of a continuous increase in event magnitude over the full record period. The anomaly in shorter duration events is attributable to two wet years in 1968 and 1970 which have not been repeated in recent years; a widespread storm on 16 August 1970 was recorded at all gauges, with 110.5 mm falling at Lough Mourne Reservoir.

Overall, the results from the rolling decadal analyses indicate increases in estimated return period magnitudes for all duration storms, particularly in the north and west. Some regions, such as NI, are dominated by extremes which occurred within a particular decade, and so the changes are less certain. The fixed return period estimates for all regions are also highly variable and dominated by exceptional events such as those of the late 1990s; however, it is not possible to attribute the cause of the variability to one single atmospheric circulation pattern.

### 4.3. Changes in seasonal rainfall

Seasonal return period estimates were examined as described above. As with the annual maxima return period estimates, there is distinct decadal variability in the results and some of the regions and seasons which were previously identified by FK2003a as significantly increased do not show a continuation of this trend. In conjunction with the increases in SMED and supporting the findings of other research (Maraun *et al.*, 2008; Allan *et al.*, 2009; Hopkins *et al.*, 2010) we find the greatest increases to be for return period estimates in autumn and winter long duration events.

As few UK annual maxima occur during the spring months (Hand *et al.*, 2004) most studies of seasonal extremes have focussed on the common sources of serious flooding, that is heavy rainfall during winter or late summer/early autumn. However, FK2003a identified increases in spring extreme rainfall over the period 1961–2000 for short-duration events around the UK, as well as in longer duration events in the north and west of the UK. Similarly, more recent work in the UK (Biggs and Atkinson, 2011) found that where the signal of change in spring maxima was previously weak or inconclusive, there is now evidence of long-term increases in the rainfall intensity. We found that estimated event magnitudes for the 10 year return period have marginally increased over the full record period in eastern regions as demonstrated in Figure 9. The trends are variable, with the largest significant increases in 5- and 10-day events and fewer significant results than for other seasons arising from the high variability.

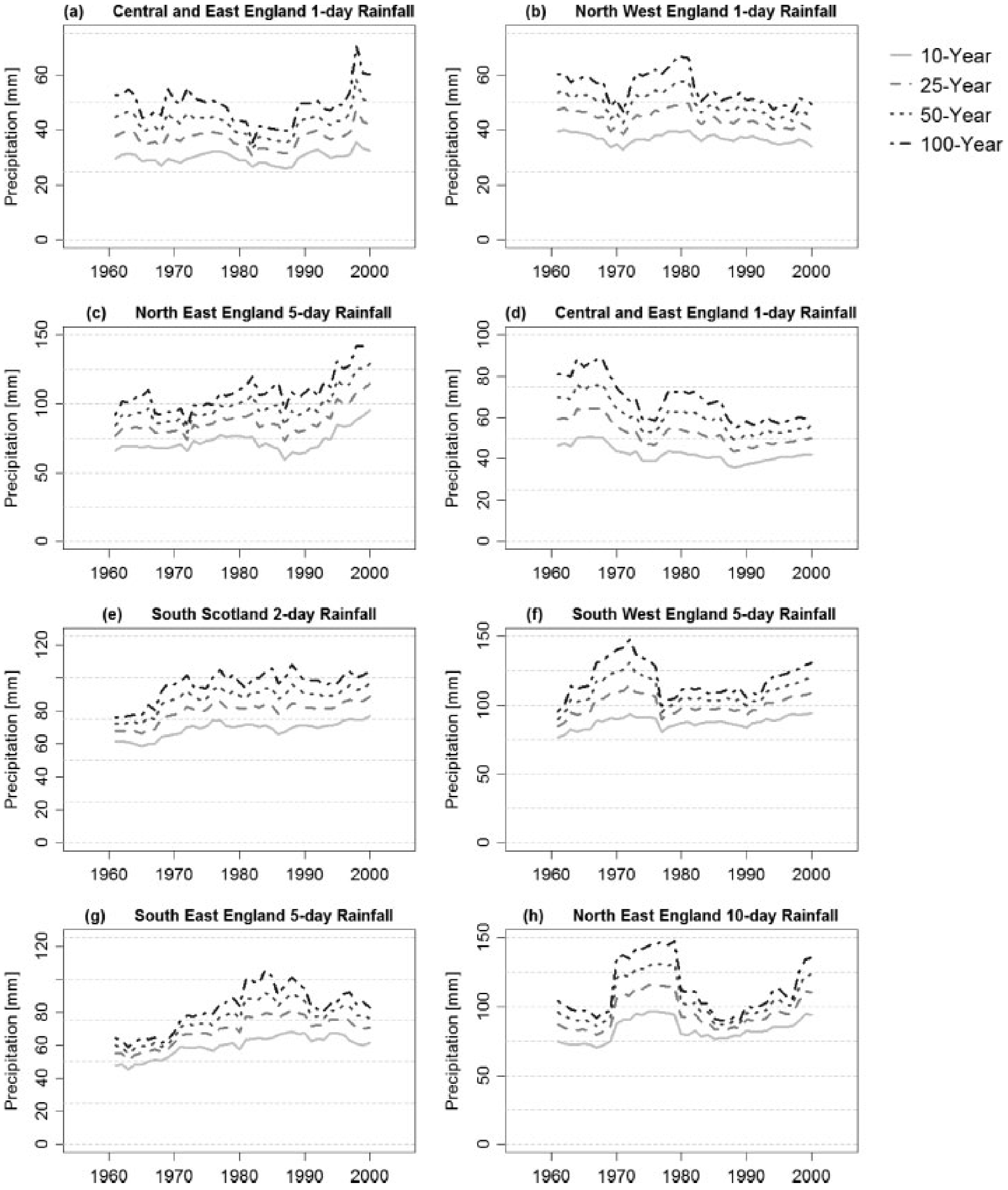

Figure 9. Ten-year rolling period return level estimates for 1961–2009 for spring (a) CEE and (b) NWE regional 1-day; summer (c) NEE 5-day, (d) CEE 1-day; Autumn (d) SS 2-day, (e) SWE 5-day; winter (f) SEE 5-day, (g) NEE 10-day.

Recent UK observations suggest that mean summer rainfall has decreased in all regions, as has the percentage contribution of the heaviest events to total summer rainfall (Jenkins *et al*., 2010). Similarly, FK2003a found that all durations of summer maxima consistently decreased in magnitude through the period 1961–2000. SMED behaviour suggests that recent summer maxima and the resultant return period estimates have continued to decrease during 2000–2009 for most regions, with minor increases in northern regions (NEE, SS, ES). With the exception of those regions, and in common with FK2003b, estimated return period magnitudes have significantly decreased in the south and east for longer duration events. Decreases of greater magnitude in the longer duration events are anticipated with increasing global mean temperature, as the limiting condition of available evaporable soil moisture will become an important factor (Allen *et al*., 2002).

Burt and Ferranti (2010) found that the contribution of heavy events to total summer rainfall had increased in the northwest corroborated here by an upward trend in estimated extreme rainfall event magnitude for 5- and 10-day durations in NI and SS. Other regional variations, such as increases in longer duration estimates in NEE

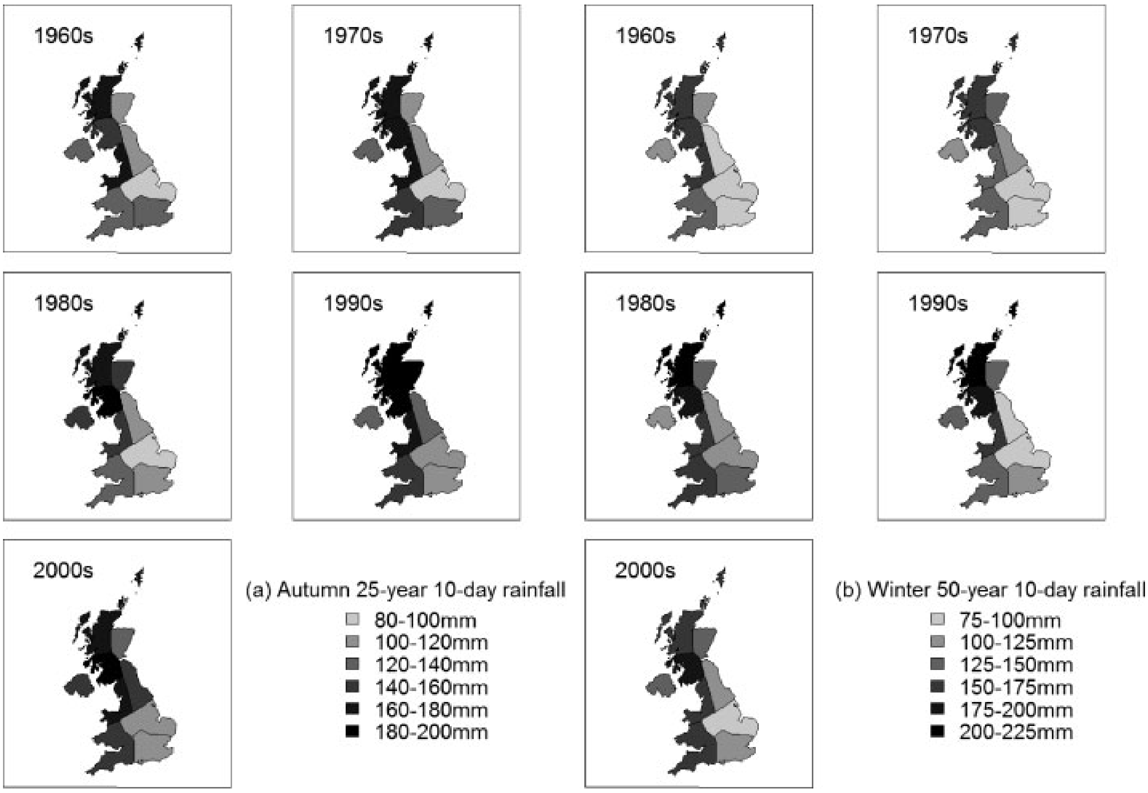

Figure 10. 10-day duration regional return period estimates from five decadal periods: (a) autumn 25-year (4% probability); (b) winter 50-year (2% probability).

and ES and little change in NS, are consistent with Perry (2006) who reported similar variability in total and maximum summer rainfall over the period 1914–2005 in approximately the same regions.

Similar to the changes in spring extreme rainfall, FK2003a found consistent increases in autumn rainfall maxima across the country, a result supported by more recent work (Maraun *et al.*, 2008; Biggs and Atkinson, 2011). Figure 10(a) demonstrates that, as with spring rainfall, the updated results have a high degree of variability from decade to decade in 25-year estimates for 10-day rainfall; with a significant increase in estimated event magnitude in all regions except NI, NWE and SEE. However, as the record for Northern Ireland is highly variable, with a corresponding irregularity in the estimated return periods, it is difficult to detect an underlying trend. In all other regions, there are increases in estimated event magnitude between the baseline period of 1961–1990 and the most recent results (Table III), although some changes are persuasive they may appear to be more significant due to the period of record examined.

The results for changes to winter extreme rainfall event magnitudes in FK2003a were spatially variable, with increases found in Scotland but little or no change found in England and Wales. Osborn and Hulme (2002) found that the proportion of rainfall from heavy events has increased during the winter season across the whole UK; this is supported for Northern Ireland and northern England by more recent research (Burt and Ferranti, 2010). Perry (2006) reported that, of all the UK regions, North Scotland experienced the largest percentage increase in winter rainfall in the period 1914–2004; increases in winter total rainfall were also found in western parts of the UK. Future projections for winter, the season most reliably reproduced by regional climate models, show estimated increases in magnitude of 15–30% across the UK for the 1-day 5-year event by 2070 (Fowler and Ekström, 2009). Similarly, the UK Climate Projections estimate a 50% probability of increases in both mean and wettest day winter rainfall in the order of 33% and 25%, respectively, for the medium emissions scenario (Murphy *et al.*, 2009).

We found that all regions exhibit a significant increase in estimated event intensity although with substantial inter-decadal variability, e.g. SWE Figure 10(b). The increase is least apparent in short-duration events in NI, CEE and NEE where summer rainfall estimates continue to dominate (Burt and Ferranti, 2010). Estimated changes in event magnitude for the 5- and 10-day 25-year events over the full record are reported in Table IV. With the exception of CEE and NI, where the changes are negligible, the results are supportive of previously observed increases in winter seasonal maxima and consequent decreases in return period estimates.

## 5. Discussion

It is always easy to determine the presence of a trend somewhere within a large data set, a phenomenon which increases in tandem with the length of record (Benestad,

Table III. Change in the estimated magnitude of 10-year and 100-year autumn rainfall events for (a) 2-day and (b) 5-day durations for the baseline period 1961–1990 and updated maxima 2001–2009, with overall trend magnitude (and significance).

| Pooling region | Rainfall from the 10 year event (mm) | | | Rainfall from the 100 year event (mm) | | |
|---|---|---|---|---|---|---|
| | 1961–1990 | 2001–2009 | Trend mm/year | 1961–1990 | 2001–2009 | Trend mm/year |
| (a) 2-day | | | | | | |
| SWE | 55.3 | 62.2 | 0.1 (0) | 74.6 | 95.5 | 0.1 (0.55) |
| SEE | 59.9 | 52.5 | −0.23 (0.01) | 99.9 | 72.9 | −0.78 (0) |
| CEE | 45.2 | 51.1 | 0.27 (0) | 67.5 | 84.7 | 0.72 (0) |
| NWE | 64.7 | 69.4 | −0.05 (0.86) | 87.7 | 99.3 | −0.02 (0.81) |
| NEE | 49.5 | 64.2 | 0.23 (0) | 66.5 | 111.5 | 0.49 (0.01) |
| NI | 65.0 | 58.9 | −0.05 (0.25) | 102.8 | 94.3 | −0.57 (0) |
| NS | 62.7 | 73.4 | 0.24 (0) | 80.2 | 103.4 | 0.57 (0) |
| SS | 61.4 | 77.2 | 0.33 (0) | 76.2 | 104.0 | 0.54 (0) |
| ES | 46.6 | 70.6 | 0.58 (0) | 61.2 | 111.9 | 1.06 (0) |
| (b) 5-day | | | | | | |
| SWE | 76.4 | 94.0 | 0.2 (0) | 95.2 | 130.6 | −0.04 (0.79) |
| SEE | 77.0 | 75.9 | −0.15 (0.04) | 113.2 | 112.9 | −0.26 (0.1) |
| CEE | 58.0 | 67.0 | 0.32 (0) | 76.5 | 98.4 | 0.69 (0) |
| NWE | 98.3 | 104.6 | 0.02 (0.81) | 134.1 | 144.6 | 0.18 (0.55) |
| NEE | 68.9 | 84.9 | 0.43 (0) | 86.5 | 136.9 | 0.99 (0) |
| NI | 89.9 | 80.4 | 0.07 (0.55) | 120.6 | 119.9 | −0.12 (0.41) |
| NS | 104.2 | 109.0 | 0.23 (0) | 134.8 | 150.9 | 0.83 (0) |
| SS | 95.6 | 114.6 | 0.8 (0) | 116.3 | 145.8 | 1.45 (0) |
| ES | 66.4 | 90.6 | 0.93 (0) | 84.2 | 129.4 | 2.02 (0) |

Table IV. Trend magnitude per year and significance in estimated event magnitude for 25-year events for 5-day and 10-day winter.

| Region | Change in 5-day magnitude (mm) | | Change in 10-day magnitude (mm) | | Estimated new return period |
|---|---|---|---|---|---|
| | mm/year | Significance | mm/year | Significance | |
| SWE | 0.31 | 0.00 | 0.68 | 0.00 | 12 year |
| SEE | 0.60 | 0.00 | 0.91 | 0.00 | 15 year |
| CEE | 0.25 | 0.00 | 0.29 | 0.00 | – |
| NEW | 0.48 | 0.00 | 0.74 | 0.00 | 8 year |
| NEE | 0.22 | 0.05 | 0.16 | 0.06 | 20 year |
| NI | 0.35 | 0.00 | 0.23 | 0.00 | – |
| NS | 0.66 | 0.00 | 1.03 | 0.00 | 30 year |
| SS | 1.28 | 0.00 | 1.23 | 0.00 | 8 year |
| ES | 0.51 | 0.00 | 0.37 | 0.00 | 12 year |

2003); however, it is more difficult to discern a consistent signal of changes across multiple regions. By using several different approaches, we have been able to identify those periods of record which were exceptional, e.g. events in NI in the early 1960s, from those which may form part of a longer term change. We also found that the influence of natural variability made some previously clear trends (FK2003a, FK2003b) more ambiguous, e.g. winter in East Scotland. Burt and Ferranti (2010) examined the trends in heavy rainfall in several long duration records for 1900–2009 across the north of England, finding significant trends in maxima for some gauges but not for others. RFA has the advantage of removing the variability across a region (i.e. individual peaks from single point observations) and allowing greater certainty in magnitude estimates for high return period events.

Methods to examine extreme rainfall can either quantify the changes in frequency of event and the relation to total rainfall, or the changes in estimated event magnitude. The former, as employed by Burt and Ferranti (2010) and references therein, is statistically interesting and useful in assessing the likely insurance risk in a year. However, in adapting to the requirements of the future, practitioners require a quantifiable assessment of changes in both frequency and likely magnitude. The approach of the current study in reviewing changes in seasonal maxima and the associated return period estimates begins to address this need.

The GEV approach to estimate the probability of different events is a well recognized tool, employed both in statistical analyses and engineering applications. A univariate analysis was used for this paper, fitted to annual and seasonal block maxima. An alternative approach would be to account for the annual cycle of rainfall using a model based on monthly maxima (Maraun *et al.*, 2009). While incorporating additional data will enhance the parameter estimates (Coles, 2001), including too many data points such as monthly maxima will introduce 'heavy' as well as 'extreme' rainfall, reducing the predictive power for higher return period events (Smith, 1987). The sinusoidal function over simplified the seasonal signal in the maxima, while improvements to the model were not balanced by its increased complexity when judged objectively using the Akaike criterion (Akaike, 1974). As a result we opted to maintain the simplicity of the univariate GEV analysis, applied to extreme rainfall.

It could be argued that the use of fixed seasons for the analyses is not appropriate if, as reported, spring and autumn are becoming shorter in duration and so maxima associated with different seasons may not be captured. Seasonal differences will vary by spring 'commencing' over a period of weeks across the country, for example. However, a fixed approach to the definition of seasons gives a benchmark against which to compare the maxima for all regions. Alternative approaches could include the use of rolling 30- or 60-day maxima, or half yearly maxima which would ignore changes in spring and autumn; as spring maxima are rarely extreme (Hand *et al.*, 2004), the latter method might be appropriate. On the other hand, the timing and magnitude of heavy rainfall events are of great consequence to farmers as newly planted crops are more vulnerable to extreme rainfall (Rosenzweig *et al.*, 2002). Furthermore, several recent devastating UK floods have occurred during the autumn and would not be effectively captured by a 6-month approach. These considerations justify the use of shorter fixed seasons in this study, leading to an earlier awareness of potential changes in behaviour.

The upward trend in autumn maxima is of particular importance to flood defence practitioners and farmers as the timing of the events may have a significant impact on harvests. The timing of autumn harvest and subsequent stubble burn in relation to extreme rainfall could also have major impacts on rural flooding by affecting surface runoff. Summertime increases in event magnitude, particularly in a hotter, drier future climate, may have devastating impacts on future floods, particularly in regions with clay soils that are more sensitive to desiccation. Similarly, many sewers in the UK have a design capacity of the 30 year event; increased urbanization coupled with more intense rainfall will lead to increases in urban flooding. Even where flooding may not be an issue, the enhanced hydrological cycle will cause an increase in 'first flush' pollution and so have a detrimental impact on river water quality.

An interesting result of this study, which requires more in-depth examination, is the influence of the NAO on the frequency and magnitude of UK heavy rainfall. While no formal analysis has been carried out to establish the relationship with the NAO, the periodic oscillations witnessed in all regional median maxima and return period estimates appear to be particularly enhanced during highly positive years, similar to the findings of other research (Hannaford and Marsh, 2008). Correlating the atmospheric drivers to the years with the largest extreme rainfall maxima would be of great interest to insurance companies who would be more prepared for high loss years.

Extension of the analyses prior to 1961 would be a valuable exercise as it would allow analysis of changes over a longer period. However, verification of the AMAX becomes more onerous with decreasing observation network density. Jones *et al.* (2010) emphasized the importance of using a spatially distributed analysis set with a minimum number of stations per regional pool; identifying at least 15 stations with an uninterrupted, reliable record becomes increasingly difficult in all regions prior to 1961. Within the resources available for this study, and given the potentially limited return from such effort, it was not possible to backdate the data set.

## 6. Conclusions

This paper has presented the updated analyses of changes in seasonal and annual maxima and the resultant estimates of regional frequency analyses previously presented by FK2003a and FK2003b, using fixed and rolling decades. An understanding of both the seasonal frequency and intensity of extreme rainfall events and trends in these is important to policy makers, engineers and insurance brokers alike in assessing future risks and appropriate actions. Similarly, determining probable future seasonal rainfall behaviour is of great concern to all involved with water resource management, from water companies to agriculture or water intensive industries.

There have been significant increases in annual maxima over the period 1961–2009, particularly in the west, confirming trends that were apparent but possibly weak in previously published work (FK2003b; FK2003a; Burt and Ferranti, 2010). Updating the previous analyses is timely, given the current focus by UK Governments and local authorities on quantifying our vulnerability to climate change; these results in combination with future projections will assist water resource managers in planning adaptation actions. Estimated return periods for South Scotland have decreased over the period of record with events formerly having a 1% annual probability now having nearer to 10% probability of occurring. In East Scotland, estimated magnitudes for 5- and 10-day events are lower than those found previously (FK2003b), but there has been a sustained increase in magnitude over the full analysis period (1961–2009) and a decrease in return period estimates from a 25-year (4% probability) to a 10-year event (10% probability).

Increases in seasonal maxima and the estimated return frequencies were found in the spring, autumn and winter seasons, emphasizing the likely increase in northern latitudes of wetter conditions (e.g. Alexander *et al.*, 2006). Results for the median summer maxima, and resultant estimates of event magnitude, are variable across the country but in general point to an increase in the highest intensity events. This result is particularly pertinent in the light of recent summer flood events, which could be set to increase in frequency if the trend of high intensity rainfall preceded by prolonged dry spells persists. Understanding the temporal link between very heavy rainfall and catchment runoff dynamics, and hence likely flood frequency, would be beneficial to adaptation planners (Wilby *et al.*, 2008), particularly as extreme impacts often arise from sequences of less severe events (Stephenson, 2008).

## Acknowledgements

We thank Claudia Underwood for providing updated daily rainfall measurements from the Rothamsted Research Archive; Tim Burt for supplying the 2000-2009 rainfall data for Durham University; Tim Osborn for the use of his daily rainfall data set for supplementary gauge records; Barry Hall for supplying the additional Met Office data; and British Atmospheric Data Centre for all other recent rainfall data. We also thank one anonymous reviewer for comments which improved the clarity of this article. This work is part of an NERC funded Postgraduate Research Studentship NE/G523498/1 (2008-2012); Dr Hayley Fowler was supported by a NERC Postdoctoral Fellowship award NE/D009588/1 (2006-2010). All analyses were performed with the statistical software R (R Core Development Team, 2011), using the ismev (Coles and Stephenson, 2006) and nsRFA (Viglione, 2011) packages.

## References

Akaike H. 1974. A new look at the statistical model identification. *IEEE Transactions on Automatic Control* **19**(6): 716–723.

Alexander LV, Jones PD. 2000. Updated precipitation series for the U.K. and discussion of recent extremes. *Atmospheric Science Letters* **1**(2): 142–150.

Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, Klein Tank AMG, Haylock M, Collins D, Trewin B, Rahimzadeh F, Tagipour A, Rupa Kumar K, Revadekar J, Griffiths G, Vincent L, Stephenson DB, Burn J, Aguilar E, Brunet M, Taylor M, New M, Zhai P, Rusticucci M, Vazquez-Aguirre JL. 2006. Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research* **111**(D5): D05109.

Allan R, Tett S, Alexander L. 2009. Fluctuations in autumn-winter severe storms over the British Isles: 1920 to present. *International Journal of Climatology* **29**(3): 357–371.

Allan RP, Soden BJ. 2008. Atmospheric warming and the amplification of precipitation extremes. *Science* **321**(5895): 1481–1484.

Allen M, Ingram W, Stainforth D. 2002. Constraints on future changes in climate and the hydrologic cycle, nature insight article. *Nature* **419**: 224–232.

Benestad RE. 2003. How often can we expect a record event? *Climate Research* **25**(1): 3–13.

Biggs EM, Atkinson PM. 2011. A characterisation of climate variability and trends in hydrological extremes in the severn uplands. *International Journal of Climatology* **31**(11): 1634–1652.

Burt TP, Ferranti EJS. 2010. Changing patterns of heavy rainfall in upland areas: a case study from Northern England. *International Journal of Climatology* **32**(4): 518–532.

Coles S. 2001. *An Introduction to Statistical Modeling of Extreme Values*. Springer-Verlag: Berlin.

Dales MY, Reed DW. 1989. *Regional Flood and Storm Hazard Assessment*, Institute of Hydrology, Wallingford, Oxfordshire.

Dessai S, Hulme M, Lempert R, Pielke R. 2009. Do we need more precise and accurate predictions in order to adapt to a changing climate? *EOS* **90**(13): 111–112.

Efron B. 1979. Bootstrap methods: another look at the jackknife. *The Annals of Statistics* **7**(1): 1–26.

Efron B, Tibshirani RJ. 1993. *An Introduction to the Bootstrap*. Chapman & Hall: London.

Faulkner DS. 1999. *Rainfall Frequency Estimation*, Wallingford, Oxfordshire.

Fowler HJ, Ekström M. 2009. Multi-model ensemble estimates of climate change impacts on UK seasonal precipitation extremes. *International Journal of Climatology* **29**(3): 385–416.

Fowler HJ, Kilsby CG. 2003a. Implications of changes in seasonal and annual extreme rainfall. *Geophysical Research Letters* **30**(13): 1720–1723.

Fowler HJ, Kilsby CG. 2003b. A regional frequency analysis of United Kingdom extreme rainfall from 1961 to 2000. *International Journal of Climatology* **23**(11): 1313–1334.

Fowler HJ, Wilby RL. 2010. Detecting changes in seasonal precipitation extremes using regional climate model projections: implications for managing fluvial flood risk. *Water Resources Research* **46**(3): W03525.

Frich P, Alexander L, Della-Marta P, Gleason B, Haylock M, Klein Tank A, Peterson T. 2002. Observed coherent changes in climatic extremes during the second half of the twentieth century. *Climate Research* **19**(3): 193–212.

Gilleland E, Katz RW. 2011. New software to analyze how extremes change over time. *EOS* **92**(2): 13–14.

Hand WH, Fox NI, Collier CG. 2004. A study of twentieth-century extreme rainfall events in the United Kingdom with implications for forecasting. *Meteorological Applications* **11**(1): 15–31.

Hannaford J, Marsh TJ. 2008. High-flow and flood trends in a network of undisturbed catchments in the UK. *International Journal of Climatology* **28**(10): 1325–1338.

Hopkins J, Warburton J, Burt T. 2010. Placing heavy rainfall events in context using long time series: an example from the North York Moors. *Weather* **65**(4): 88–94.

Hosking JRM, Wallis JR. 1988. The Effect of Intersite Dependence on Regional Flood Frequency Analysis. *Water Resources Research* **24**(4): 588–600.

Hosking JRM, Wallis JR. 1997. *Regional Frequency Analysis: An Approach Based on L-Moments*. Cambridge University Press: Cambridge, UK.

Institute of Hydrology. 1999. *Flood Estimation Handbook (Procedures for Flood Frequency Estimation)*, Institute of Hydrology: Wallingford, Oxfordshire.

Jenkins G, Perry M, Prior J. 2010. The climate of the UK and recent trends. [Online]. Available at: http://ukclimateprojections.defra.gov.uk/content/view/816/500. (Accessed: 23/03/11).

Jones MR, Fowler HJ, Kilsby CG, Blenkinsop S. 2010. *An Updated Regional Frequency Analysis of United Kingdom Extreme Rainfall 1961–2009*. In *Proceedings of BHS 2010: Role of Hydrology in Managing Consequences of a Changing Global Environment.* Newcastle, UK, 19–23 July 2010. BHS Third International Symposium, 110–118.

Jones PD, Conway D. 1997. Precipitation in the British Isles: an analysis of area-averaged data updated to 1995. *International Journal of Climatology* **17**(4): 427–438.

Karl TR, Trenberth KE. 2003. Modern global climate change. *Science* **302**(5651): 1719–1723.

Krebs J, Dlugolecki A, Fankhauser S, Hall JW, Johnson A, Palmer T, Parry M, Wynne G, Young B. 2010. *How Well Prepared Is the UK for Climate Change?* Adaptation Sub-Committee: London.

Liu B, Henderson M, Xu M, Zhang Y. 2011. Observed changes in precipitation on the wettest days of the year in China, 1960–2000. *International Journal of Climatology* **31**(4): 487–503.

Maraun D, Osborn TJ, Gillett NP. 2008. United Kingdom daily precipitation intensity: improved early data, error estimates and an update from 2000 to 2006. *International Journal of Climatology* **28**(6): 833–842.

Maraun D, Rust HW, Osborn TJ. 2009. The annual cycle of heavy precipitation across the United Kingdom: a model based on extreme value statistics. *International Journal of Climatology* **29**(12): 1731–1744.

McEvoy D, Matczak P, Banaszak I, Chorynski A. 2010. Framing adaptation to climate-related extreme events. *Mitigation and Adaptation Strategies for Global Change* **15**(7): 779–795.

Milly PCD, Betancourt J, Falkenmark M, Hirsch RM, Kundzewicz ZW, Lettenmaier DP, Stouffer RJ. 2008. Climate change: stationarity is dead: whither water management? *Science* **319**(5863): 573–574.

Murphy JM, Sexton DMH, Jenkins GJ, Boorman PM, Booth BBB, Brown CC, Clark RT, Collins M, Harris GR, Kendon EJ, Betts RA, Brown SJ, Howard TP, Humphrey KA, McCarthy MP, McDonald RE, Stephens A, Wallace C, Warren R, Wilby R, Wood RA. 2009. *UK Climate Projections Science Report: Climate Change Projections*. Met Office Hadley Centre: Exeter.

Nelson DR. 2011. Adaptation and resilience: responding to a changing climate. *Wiley Interdisciplinary Reviews: Climate Change* **2**(1): 113–120.

Osborn TJ, Hulme M. 2002. Evidence for trends in heavy rainfall events over the UK. *Philosophical Transactions: Mathematical, Physical and Engineering Sciences* **360**(1796): 1313–1325.

Pall P, Allen M, Stone D. 2007. Testing the Clausius–Clapeyron constraint on changes in extreme precipitation under Co2 warming. *Climate Dynamics* **28**(4): 351–363.

Perry M. 2006. *A Spatial Analysis of Trends in the UK Climate since 1914 Using Gridded Datasets*. Met Office: Exeter, UK.

Portmann RW, Solomon S, Hegerl GC. 2009. Spatial and seasonal patterns in climate change, temperatures, and precipitation across the United States. *Proceedings of the National Academy of Sciences* **106**(18): 7324–7329.

Pryor SC, Howe JA, Kunkel KE. 2009. How spatially coherent and statistically robust are temporal changes in extreme precipitation in the contiguous USA? *International Journal of Climatology* **29**(1): 31–45.

R Development Core Team. 2011. *R: A Language and Environment for Statistical Computing*.

Rosenzweig C, Tubiello FN, Goldberg R, Mills E, Bloomfield J. 2002. Increased crop damage in the US from excess precipitation under climate change. *Global Environmental Change* **12**: 197–202.

Smith RL. 1987. Estimating tails of probability distributions. *Annals of Statistics* **15**: 1174–1207.

Stephenson DB. 2008. *Definition, Diagnosis, and Origin of Extreme Weather and Climate Events*. Cambridge University Press: Cambridge, UK. 348 pp.

Trenberth KE, Dai A, Rasmussen RM, Parsons DB. 2003. The changing character of precipitation. *Bulletin of the American Meteorological Society* **84**(9): 1205–1217.

Trenberth KE, Jones PD, Ambenje P, Bojariu R, Easterling D, Klein Tank A, Parker D, Rahimzadeh F, Renwick JA, Rusticucci M, Soden B, Zhai P. 2007. Observations: surface and atmospheric climate change. In *Climate Change 2007 the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change 2007*, Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds). Cambridge University Press: Cambridge, United Kingdom and New York.

Viglione A. 2011. Non-Supervised Regional Frequency Analysis (0.7–2).

Villarini G, Smith JA, Baeck ML, Vitolo R, Stephenson DB, Krajewski WF. 2011. On the frequency of heavy rainfall for the midwest of the United States. *Journal of Hydrology* **400**: 103–120.

Wigley TML, Lough JM, Jones PD. 1984. Spatial patterns of precipitation in England and Wales and a revised, homogeneous England and Wales precipitation series. *International Journal of Climatology* **4**(1): 1–25.

Wilby RL, Beven KJ, Reynard NS. 2008. Climate change and fluvial flood risk in the UK: more of the same? *Hydrological Processes* **22**(14): 2511–2523.

World Meteorological Organization. 2009. Guidelines on analysis of extremes in a changing climate in support of informed decisions for adaptation. In Tank AK, Zwiers FW, Zhang X (eds). Geneva, Switzerland. *World Meteorological Organization* pp. 55.

Yue S, Pilon P. 2004. A comparison of the power of the *T* test, Mann-Kendall and Bootstrap tests for trend detection. *Hydrological Sciences Journal* **49**(1): 1–37.

Zhang X, Hegerl G, Zwiers FW, Kenyon J. 2005. Avoiding inhomogeneity in percentile-based indices of temperature extremes. *Journal of Climate* **18**(11): 1641–1651.